IMPLICATIONS OF HYBRID DECENTRALIZED ENERGY SYSTEMS COMPOSED OF SOLAR PHOTOVOLTAICS AND COMBINED COOLING, HEATING AND POWER (CCHP) SYSTEMS WITHIN LARGE URBAN REGIONS

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IMPLICATIONS OF HYBRID DECENTRALIZED ENERGY SYSTEMS COMPOSED OF SOLAR PHOTOVOLTAICS AND COMBINED COOLING, HEATING AND POWER (CCHP) SYSTEMS WITHIN LARGE URBAN REGIONS

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To my mom who taught me I could do anything and has supported me throughout.

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LIST OF ABBREVIATIONS

BOS	Balance of System
CCHP	Combined Cooling Heating and Power
CCNG	Combined Cycle Natural Gas
HET	Hybrid Electric Thermal
FEL	Follow the Electric Load
FIT	Feed in Tariff
FTL	Follow the Thermal Load
HRU	Heat Recovery Unit
NPV	Net Present Value
PGU	Primary Generating Unit
PV	Photovoltaic

SUMMARY

Increasing urbanization places cities at the forefront of achieving global sustainability. Urban regions play a major role in the global economy and are responsible for a majority of global resource consumption. Water and energy are the two main growth-limiting resources of an urban region and are highly interdependent. An increase in urbanization means increasing demand for water, energy, and their associated infrastructure systems. Greater demand for provision of water and energy resources is associated with an increase in the emissions and wastes generated to supply these resources. Therefore, in order for urban areas to become more sustainable, they must meet the increasing demands on resources through increased efficiency, resilience and sustainable alternatives. Decentralized energy systems have the potential to improve the resiliency and efficiency of energy generation in an urban region while reducing the emissions created. Combined cooling, heating and power (CCHP) systems are more efficient than conventional energy generation systems as they can simultaneously generate electricity, useful heat, and cooling. Adding solar photovoltaics to this system will further decrease the emissions and water consumption that result from the energy generation process. The objective of this work was to determine the efficacy of implementing CCHP systems, with and without solar photovoltaics, for five generic building types in the Atlanta metropolitan region, and the economic and environmental impacts of these systems under various follow the thermal load operational strategies. CCHP systems were modeled using air-cooled microturbines and absorption chillers to match the thermal (heating, cooling, and hot water) load of the 5 building prototypes. The 5 prototypes consisted of 3 commercial and

2 residential buildings. The CCHP systems were modeled to operate under various thermal loading strategies to determine the best strategy to minimize costs, emissions, and water consumption for energy generation. The prototype buildings were then used to estimate the projected energy consumption of residential and commercial buildings in the 13-county Atlanta metropolitan region and determine the emissions and water for energy impact of conventional versus CCHP energy generation systems. Solar photovoltaics were then added to the CCHP system to determine the optimum PV area required for a given building and how this changes based on the feed in tariff. We found that operating microturbines to follow the hourly thermal load of a given building results in the greatest reduction in CO_2 emissions, and operating the turbine constantly to meet the maximum annual thermal demand results in the greatest NO_x and water for energy reductions. A net metering policy will impact the which operational strategy produces the greatest reductions in emissions, water for energy, and cost. When applied to the 13-county Atlanta Metropolitan region, CCHP systems can significantly reduce emissions and water for energy consumption. For all building types, the economic feasibility of implementing solar photovoltaic systems with microturbines is dependent on the discount rate of the system, the cost of the solar-pv system, the feed-in tariff rate, and if various policies are implemented to provide benefits for the mitigation of CO_2, NO_x, and water consumption. A cost reduction of $0.50/kW to $0.70/kW could make the PV system economically feasible for all building types if a feed-in tariff policy, based on the price of electricity for the given building type, is also in place.

CHAPTER 1

INTRODUCTION

Cities are responsible for more than 70% of global energy use and responsible for ~50% of global greenhouse gas emissions[1]. The World Bank estimates that cities are accountable for more than 80% of the global GDP[2]. Because the proportion of the global population currently living in cities is expected to increase to at least 66% by 2050, cities and global organizations are looking for ways to improve efficiency and decrease their environmental impact[3]. There are three main concerns for cities relating to growth: energy demand, water management, and energy-related emissions (CO_2 and NO_X) reduction. Combined cooling, heating and power (CCHP) systems have the potential to improve the efficiency of energy generation, thereby affecting the primary energy use, water consumption, and emissions output of cities.

As the population of an urban region increases, the policies, planning and design of the region can determine the effect and impact of urban sprawl, which can amplify the effect of water and energy losses in the region.[4] The amplified losses are due to inefficiencies in treatment, generation and distribution systems. In 2005, approximately 7 billion gallons per day, or 16% of the U.S. total potable water supply was lost as a result of leaks in the water distribution system[5, 6]. The electrical infrastructure of the US is aging and degrading, resulting in energy losses within the system[5]. It is estimated that approximately $57 billion will need to be invested by 2020 to adequately meet the demand of the population [5]. In 2011, electricity generation accounted for approximately 40% of the energy use in the US [7]. Two-thirds of the electricity generated was lost as heat and 6.5% of the electricity generated was lost due to transmission and distribution inefficiencies[8]. Electrical distribution system losses result in the loss of approximately 0.13 gallons of water per kWh from the average U.S. power production plant[9]. The implementation of decentralized energy alternatives would be a valuable option to meet the demand of the increasing urban population while reducing losses in the system. The purpose of this dissertation is to examine the economic and environmental impacts that implementing a CCHP system or a hybrid PV-CCHP system can have on an urban region, using Atlanta as a case study. We also investigate policy scenarios that can help improve the economic viability of each case.

Background of Research

Combined cooling, heating and power (CCHP) systems

Combined cooling, heating and power (CCHP) systems have greater efficiency than conventional energy generation systems as the heat generated during the combustion process is used to meet some of the building heating and cooling requirements, instead of being wasted. The combined efficiency (electricity + heat) of CCHP systems is approximately 75% as compared to approximately 50% (combined-cycle natural gas power plants) for conventional energy generation systems[10]. Conventional energy generation systems for buildings (Figure 1) are comprised of electricity from the central electricity grid and heat from a furnace or boiler[11, 12]. Typical CCHP systems are composed of a microturbine, a heat recovery unit (HRU), and an absorption chiller (Figure 1). The microturbine is the power generating unit (PGU) of the system and generates electricity and heat, and the absorption chiller is able to convert the heat provided by the PGU to cool the building when required. The heat recovery unit (HRU) takes the exhaust heat provided by the PGUs and uses it to provide hot water and space heating. The increased efficiency in energy generation translates into reduced emissions and reduced 'water for energy' consumption. The implementation of CCHP systems can have a tremendous impact on a city due to the increased energy efficiency, lower 'water for energy' footprint, lower emissions and improved air quality.

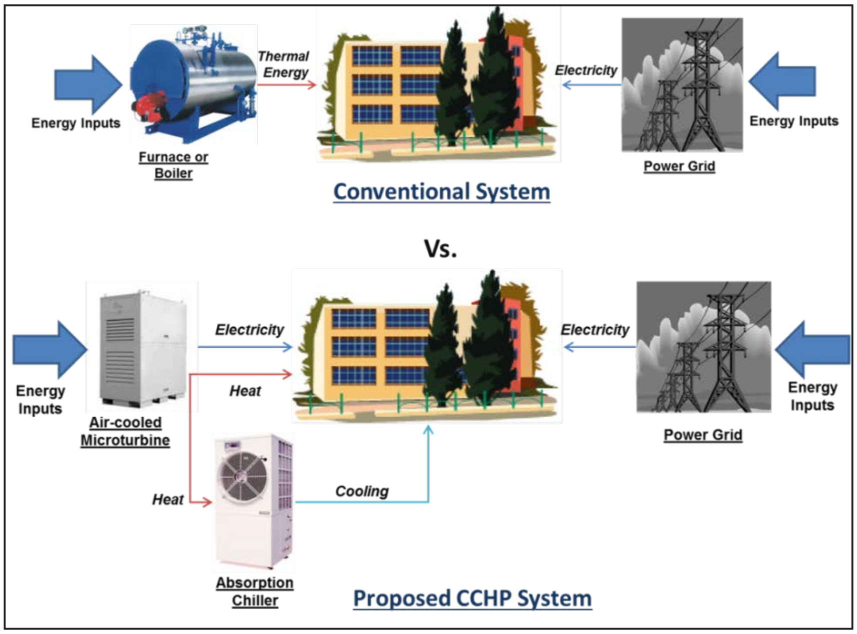

Figure 1. Combined Cooling, Heating and Power (CCHP) System

The implementation of CCHP systems is of particular importance to cities or urban regions that currently, or might soon, face issues of water scarcity[13]. Atlanta is one such urban region. The Atlanta metropolitan region is one of the fastest growing metropolitan regions in the U.S.[14]. In Georgia, approximately 49% of the water withdrawal is used for thermoelectric power[15]. With an estimated 55% of the state's population living within the Atlanta metropolitan region, a significant portion of the 'water for energy' generation can be attributed to the metropolis[15, 16]. The continued urban sprawl in Atlanta, combined with the inefficiencies and losses associated with traditional energy generation, will continue to increase the energy and water demand and energy-related emissions [17]. Implementation of CCHP systems can increase the efficiency of the energy generation system and thereby reduce the emissions and 'water for energy' consumption of the region. Having a decentralized energy production system also increases the redundancy within the energy production system of a region, thereby increasing its resiliency.

There have been many studies on the benefits of CCHP systems and the most effective ways to reduce cost, primary energy consumption, and carbon emissions [18, 19]. CCHP systems can be designed to reduce the primary energy consumed [20-23], the cost and carbon footprint of energy applications [18, 24-26], or some combinations thereof. Two strategies that have been widely used when modeling the operation of CCHP systems are: "following the electrical load" [27] (FEL) and "following the thermal load" (FTL). Most of the research that has been conducted on the use of CCHP systems have examined how various load options mentioned above can best optimize the system to reduce cost, primary energy consumption, and carbon emissions. Previous studies have concluded that a "hybrid electric thermal" (HET) approach, which switches between FTL and FEL in order to reduce the amount of excess heat and energy, is closer to the optimum operation [28]. Han et al. modified the HET approach even further by using a multi-objective optimization model [29]. Changing the number and type of energy generating units were considered, as well as splitting the operation of the turbines into 2 components. One component meets a base load and the other component meets FEL or FTL [30].

The operation of CCHP systems in different climatic conditions and the tradeoffs in cost and carbon emissions reductions was explored by Cho et al [31]. The power-to-heat ratios and, portion of electrical energy to heat energy of various building types also affects how effective a CHP systems is at to optimizing the reduction of energy consumption, cost of energy, and emissions [32]. The effects of energy management also impact the efficiency of the overall system and therefore the cost and number of units required [33].

Combined cooling, heating and power (CCHP) systems have greater efficiency than conventional energy generation systems, as the heat generated in the combustion process is used to meet some of the heating requirements of the building instead of being wasted using cooling towers and evaporating water. CCHP systems require less energy input than conventional energy generation systems to deliver the same amount of cooling, heating and electrical energy. The efficiency of CCHP systems is approximately75% compared to about 50% for conventional energy generation systems[10]. Conventional generation systems comprise of electricity from the central grid system and heat from a furnace or boiler[11, 12]. CCHP systems can be composed of a turbine, heat recovery unit (HRU), and absorption chiller. The microturbine is the power generating unit (PGU) of the system and generates electricity and heat, and the absorption chiller is able to convert the heat provided by the PGU to cool the building. The heat recovery unit (HRU) takes the exhaust heat provided from the PGUs and converts it to heat water and as well as the building itself. The increased efficiency in energy generation translates into reduced emissions and reduced water for energy consumption. The implementation of CCHP systems could have a tremendous impact on a city due to the increased energy efficiency, and can in turn generate fewer emissions and improve air quality.

Implementing large scale decentralized CCHP systems

The implementation of CCHP systems is of particular importance to cities or urban regions that already, or might soon, face issues of water scarcity[13]. Atlanta is one such urban region. The Atlanta metropolitan region has been ranked as one of the fastest growing metropolitan regions in the U.S.[14]. In Georgia, approximately 49% of the water withdrawn is used for thermo-electric power, and with an estimated 55% of the state's population living within the Atlanta metropolitan region, a significant portion of the water for energy generation can be attributed to the metropolis[15, 16]. Continued urban sprawl in Atlanta will impact the energy demand and emissions from energy in terms of amplified inefficiencies and energy losses [17]. Implementation of CCHP systems could increase the efficiency of the energy generation system and impact the emissions and water for energy consumption of the region.

CCHP and Solar PV

Solar photovoltaic (PV) technology is the most prevalent and clean renewable energy technology available and is seen as a way to meet our energy demand without increasing environmental pollution from energy generation [34]. Solar energy use is also gaining popularity world-wide as the efficiency of the technology increases and the market for PV systems becomes more competitive. PV systems are able to convert sunlight to electrical energy and are a viable solution for decreasing emissions [35]. Currently the two main deterrents for the implementation of PV systems are cost of the system and the variability of generation [36]. The current costs of the system reduce the economic feasibility of implementation as they are higher than the costs of current centralized energy generation systems [36].

Considerable work has been conducted on the efficacy of various hybrid PV-CHP systems [37-42]. Two main types of hybrid systems have been analyzed – hybrid PV-thermal (PVT) and hybrid PV-CHP/CCHP [43-45]. Previous studies have looked at hybrid PV- thermal (PVT) systems in which waste heat is recovered from the panels but, the intermittency of PV generation in such systems still posed an issue [46]. The PV industry for has been rapidly changing in the last few years and, with the incorporation of battery storage, some of the issue of intermittency is no longer a deterrent for installing solar systems [47]. Implementing taxes on the emissions from energy generation will both decrease the total amount of emissions produced and increase the economic feasibility of PV [35]. Studies typically consider CHP systems as a backup to solar; however, in our study, the CCHP system is operated to meet the thermal load (heating, cooling, hot water) of a building and the PV system supplies additional electricity not provided by the CCHP system[35] .

Research Objectives

The goal of this research is to examine the efficacy of implementing hybrid decentralized energy systems to reduce the economic and environmental impacts of energy generation within an urban region.

The specific objectives are:

1) To determine the best operation strategy of a CCHP system following the thermal load of for five building prototypes, when considering the maximum possible reduction of: CO2 emissions, NOx emissions, water consumption for energy generation, and cost.

2) To determine if and how a net metering policy would impact operational strategy and maximum potential reduction in CO2 emissions, NOx emissions, water consumption for energy generation, and cost for all building types.
3) To estimate the impact CCHP systems can have if implemented in a large-scale urban growth projection.
4) To determine the optimum PV size for all building prototypes under a range of feed-in tariffs and if no optimum can be found, determine the breakeven costs for each building type.
5) To determine what the optimum PV size would be for a hybrid PV-CCHP system, and how monetizing the emissions savings and water consumption for energy production would change the optimum PV system size.

CHAPTER 2

ENVIRONMENTAL AND ECONOMIC IMPACTS OF AIR-COOLED MICROTURBINES FOR COMBINED COOLING, HEATING AND POWER (CCHP) SYSTEMS

The objective of this section is to estimate the efficacy of implementing combined cooling, heating and power systems for five generic building types in the Atlanta region, looking at the "water for energy" , environmental, and economic impacts and how different loading strategies affect these impacts.

Methodology

Our CCHP system consists of an air-cooled microturbine and an absorption chiller (see Figure 1) that is used to meet the heating and cooling load of a building. In this case, the thermal load of the building consists of the sum of the energy required for space-heating, cooling and hot water. The CCHP system was designed to be a "follow the thermal load" (FTL) model; systems of this type have been shown to have lower emissions and lower costs than following the electrical load of the building [28, 48]. Five scenarios were tested to see which would most significantly decrease emissions, 'water for energy' and cost. Each scenario is a variation of how the microturbine was operated to meet the hourly, maximum daily, maximum monthly, and maximum yearly thermal demands of the buildings.

Capstone air-cooled microturbines were considered for this analysis as they use air-cooling rather than water-cooling. Capstone currently commercially manufactures 30 kW, 65 kW and 200 kW air-cooled microturbines. Combinations of these turbines were also evaluated. The three combination turbines modeled were 95 kW (65 and 30 kW turbines), 130 kW (two 65 kW turbines) and 160 kW (two 65 kW and one 30 kW turbine). The thermal outputs of the turbines, running at various capacities, were determined using the technical manuals provided by the manufacturer. In the case of the combination turbines it is assumed that the largest turbine in the combination is ramped up first until it reaches 100% capacity. The process is repeated for each subsequent turbine added until the thermal demand is met. Each thermal output for a given turbine corresponds to a given electrical output, and fuel input requirements. The operating schedule of the turbines were simulated to meet the hourly, maximum daily, maximum monthly, and maximum yearly thermal loads of the five buildings being considered and this is shown in Appendix A.

In each of the cases the turbine or combination of turbines was always able to meet the thermal load of the building. Therefore, the size of the turbine remained the same for a given building type regardless of the scenario that was run.

Reference Buildings and Energy Supply Options

Five building types were used in the analysis: three commercial and two residential buildings. The three commercial buildings ranged in size from small (5500 sq.ft) to large (500,000 sq.ft), and the two residential buildings were a single-family house and a multifamily apartment building. Table 1 details some of the buildings' characteristics, specifications, and heating and cooling equipment used for conventional heating and cooling. The thermal load of the single family and small office buildings were too low for even the smallest turbine (30 kW). Therefore, we calculated that a single 30 kW turbine would always be able to meet the thermal demand of 5 single family buildings and 2 small office buildings. This was calculated by dividing the maximum hourly thermal output of the turbine by the maximum hourly thermal output of the given building. All subsequent uses of “single-family” and “small office” refer to 5 single family and 2 small office buildings, respectively.

The building energy load profiles for Atlanta were obtained from the Open Energy Information (OpenEI) website [49]. The energy demands were generated from Energy Plus simulations of the U.S. Department of Energy commercial reference building models using the TMY3 weather file for the Atlanta region [50].

Table 1: Characteristics of reference buildings and conventional energy systems [49]

Building type	Square footage	# of floors	Heating Equipment (Cost[51])	Cooling Equipment (Cost[51])	Building electrical demand(kWh)[cooling+ plug load]	Building heating demand (kWh)	Turbine size (kW)
Large office	500000	12	Boiler	Chiller, water-cooled-mz	6963487	419346	2000
			($9.85/sqft)				
Medium office	53628	3	Boiler	Packaged DX-mz	728547	18019	130
			($17.45/sqft)				
Small office	5500	1	Furnace	Packaged DX-sz	68171	7447	30 for 2 buildings
			($9.25/sqft)				
Multifamily residential	33740	4	Furnace	Packaged DX-split system-sz	258790	107795	65
			($6.39/sqft)				
Single family residential	2546	1	Furnace	Single packaged	12740	10342	30 for 5 buildings
			($6975)				

We determined the building’s heating, cooling and electrical energy demands for the conventional energy system and the CCHP system using the OpenEI datasets for building energy demand. The building energy demand and input energy requirements for a small office building using a conventional and CCHP system are shown in Figure 2.

The building electrical and thermal energy demand, when using the conventional energy system, was calculated using equations 1 and 2 respectively. For the conventional energy system, the building electrical demand will need to be met entirely by the electrical grid. The annual energy input required by a building using the conventional energy system was determined by dividing the electrical load, determined in equation 1, by the efficiency of the electrical grid and dividing the thermal load in equation 2 by the efficiency of the heating equipment. The annual thermal and electrical energy inputs for a building using a conventional energy system were then added to determine the total energy inputs required by the building. Energy supply for conventional operation is shown in Figure 2b.

$$Electrical\ demand_{conventional} = plug\ load\ + cooling_{Space} \quad (1)$$

$$Thermal\ demand_{conventional} = heating_{space}\ + heating_{hot\ water} \quad (2)$$

The energy demand when using the CCHP system was determined using equations 3 and 4. The electrical demand when using a CCHP system is the plug load (equation 3). The thermal load, when using a CCHP system, is the sum of the energy required for space heating, hot water, and heat energy required for the absorption chiller for space cooling. The absorption chiller is able to convert heat energy into cooling energy. The heat energy required by the absorption chiller is determined using the ratio of coefficient of performance (COP) of the air conditioner and absorption chiller. The COP of the air conditioning units were assumed to be 3.8, which is the minimum allowable seasonal energy efficiency ratio of 13 and the COP of a double effect absorption chiller used is 1.42 [52-55]. The annual input energy required was calculated by determining the input energy that would be required from the electrical grid and input energy required by the CCHP system. The input energy required by the CCHP system was determined using the manufacturer's technical document of the fuel required for a turbine running at a given capacity. The electrical energy required from the grid is the electricity demand of the building minus the electricity produced by the turbine (equation 5). The energy input required by the electrical grid system is the electricity required from the electrical grid divided by the efficiency of the grid generation and distribution system. The energy that was required for CCHP operation for a small office building is shown in Figure 2c.

$$Electrical\ demand_{CCHP} = plug\ load \quad (3)$$

$$Thermal\ demand_{CCHP} = heating_{space} + heating_{hot\ water} + \frac{COP_{Air\ Conditioner}}{COP_{Absorption\ Chiller}} * cooling_{Space} \quad (4)$$

$$Electrical\ grid\ demand_{CCHP} = Electrical\ demand_{CCHP} - turbine_{elec} \quad (5)$$

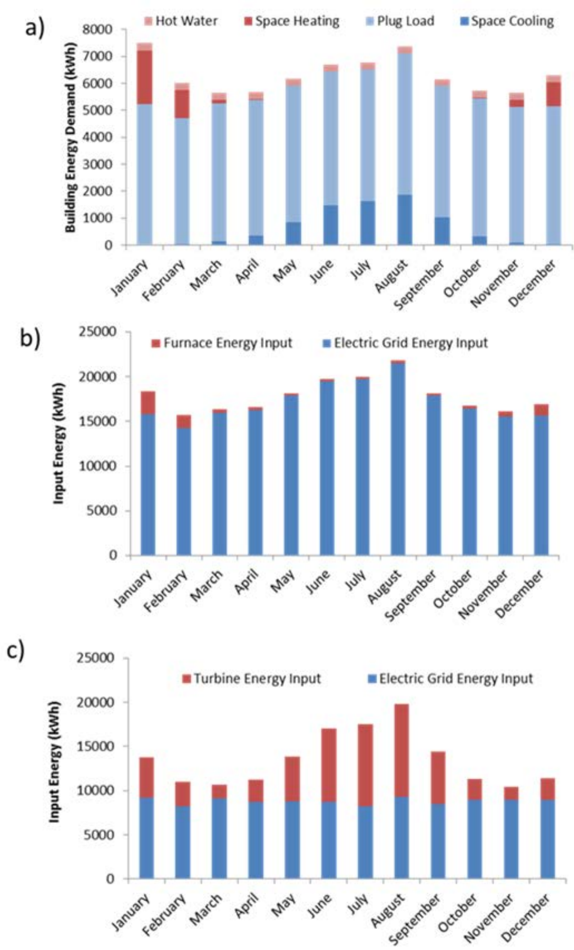

Figure 2: Energy requirements of a small office building in the Atlanta region: a) Small office building energy requirements. b) Input energy requirements of a small office building using a conventional energy generating and distribution system. c) Input energy requirements of a small office building on a CCHP system.

CCHP System Operation

There are five scenarios for a building's operation: 1) No CCHP, 2) turbines run to meet the hourly thermal demand, 3) turbines run to meet the maximum daily demand, 4) turbines run to meet the maximum monthly demand, and 5) turbines run at the annual maximum thermal demand throughout the year. The hourly thermal load was calculated from the modified OpenEI dataset using Equation 3 and correspondingly adjusting electrical demand. The input data for scenarios 3-5 were produced, using the modified hourly dataset for a building. The maximum daily thermal demand was determined by finding the maximum thermal demand for every day in the modified hourly thermal dataset and setting this as the thermal demand of the building for the day. The maximum monthly and maximum annual demands were determined in a similar fashion for a given month and for the year. Appendix A describes how the turbines were operated compared to the demand of the building and operation schedule. For each building type and scenario the “water for energy” consumption, CO_2 emissions, NOx emissions, and system costs were estimated. The turbines were modeled to ramp up and down to meet the demand profile required for the four scenarios that included a CCHP system. Turbine size was chosen based on the smallest sized turbine that was able to meet the maximum thermal load required by the building. Since the thermal load is met by the microturbine, no boiler or furnace is required if a CCHP system is used. All scenarios will require energy from the grid but the amount will depend on how the turbines are operated. The absorption chiller for each building was sized to satisfy the cooling requirement of the building.

“Water for energy” and emissions

The average CO_2 and NOx emissions per kWh from the Atlanta generation mix are shown in Table 2, using 2012 and 2013 data. These emissions can be expected to change as new power generation replaces older less efficient plants. Choi and Thomas [56] have calculated that greenhouse gas emissions per kWh in Georgia will fall over time as the new nuclear power plants are completed and planned retirements of coal-fired power plants are completed. NOx emissions are also expected to continue to fall over time as air pollutant emission reductions are implemented. For this study the CCHP emissions were compared to the emissions of the current Atlanta energy generation mix. Emissions from the furnace, and the emissions from the microturbine were calculated using data provided by the manufacturer [57-59]. Water used for cooling in the production of electricity includes both water that is withdrawn and subsequently returned to the watershed (e.g. in once-through cooling systems) and water that is evaporated (e.g. in evaporative cooling). Water consumption for energy generation was calculated using the average consumption factor for the Georgia grid as1.65 gallons per kWh. A secondary analysis compared the CCHP scenarios to one in which the the energy required from the grid was met by a combined cycle natural gas plant using a factor of 0.2 gallons per kWh [60], which may be more typical of marginal consumption. Equations 6 and 7 illustrate what factors were included in the emissions for scenarios with CCHP versus without.

Table 2. Emissions generation and water for energy consumption factors

	CO_2e Emissions (kg/kWh)	NOx Emissions (g/kWh)	Water for Energy Consumption (gallons/kWh)
Microturbine	0.768[57]	0.29[57]	-
Conventional electric grid	0.57[61]	0.408[62]	1.65[63]
Furnace	0.227	0.425[58]	-
CCNG	0.515	0.3[64]	0.2[65]

$$Emissions_{conventional\ net} = Emissions_{grid} + Emissions_{Furnace} \quad (6)$$

$$Emissions_{CCHP\ net} = Emissions_{grid} + Emissions_{Turbine} \quad (7)$$

Cost estimates

The costs of the no CCHP scenario in which all energy is coming from the electric grid and furnace, were calculated using the Georgia Power price of electricity [66] and price of natural gas in Georgia for residential and commercial customers(Table 3)[67]. The cost of the CCHP systems were estimated using the range from published literature and the costs for furnace and HVAC system were estimated using the RS means data set [51, 68]. There may be installation costs over and above these values, which should be considered for individual project evaluation. The capital cost of the CCHP equipment was amortized for the yearly cost using a discount rate of 5% and a system lifetime of 10 years [69]. The annual HVAC systems cost were determined using a similar discount rate and a system lifetime of 15 years. The capital cost of the absorption chiller was estimated using the range of values provided in the literature and the estimated lifespan of 20 years [70]. Since the CCHP system consists of the microturbine and the absorption chiller the overall CCHP system lifetime was assumed to be 10 years with an interest rate of 5%. Two capital costs were calculated for the CCHP system using the minimum and maximum range of costs provided for the microturbine and absorption chiller. The total cost per year for each building in each scenario was estimated by summing the annual fuel costs and the annual capital costs for each system (equations 8 and 9). The capital costs incurred by the utilities are incorporated in the per kWh price paid for electricity generation. It is assumed that these will be new buildings and so the costs compare conventional technologies to that of the CCHP system.

$$Cost_{conventional\ net} = (Elec_{used} * P_{Elec}) + (Nat\ Gas_{used} * P_{natural\ gas}) + P_{AC\ annual} + P_{furnace\ annual} \quad (8)$$

$$Cost_{CCHP} = (Elec_{used} * P_{Elec}) + (Nat\ Gas_{used} * P_{\ natural\ gas}) + P_{Turbine\ Annual} + P_{\ Chiller\ Annual} \quad (9)$$

Table 3: Costs of CCHP system components and fuels

Microturbine	Capital ($/kW)	700-1100 [71]
	O&M ($/kWh)	0.005-0.016 [71]
Absorption Chiller	Capital ($/kW)	140-290 [70]
	O&M ($/kW/yr)	4.5-9 [70]
Natural Gas	Residential ($/kWh)	0.049815[67]
	Commercial ($/kWh)	0.032[67]
	Utility ($/kWh)	0.015[67]
Grid Electricity	Residential ($/kWh)	0.1255[66]
	Commercial ($/kWh)	0.1044[66]

Net Metering

Within each of the five scenarios, the impact of a net metering policy on the system was evaluated. Net metering is the ability to sell excess electricity generated to the grid. For scenarios with net metering, the electricity available to sell back to the grid was determined by finding the difference between the electricity generated by the CCHP system and the electricity demand of the building. The excess electricity is generated when, at a given hour, the electricity produced by the turbine surpasses the electricity required by the building. The water consumed during energy production for the CCHP system and for traditional systems was calculated using the estimates listed in Table 2. As stated previously, the microturbine is air-cooled and therefore does not consume any water. It was assumed that when a net metering policy is implemented the water consumed for energy produced by the power grid is mitigated, since a portion of the electricity will be provided by the CCHP system.

Results and discussion

In order to reduce overall energy use through use of a CCHP system, the system needs to be run to meet the building's hourly thermal load, with additional electricity purchased from the grid to meet the full electrical requirements of the building. Under this operating scenario, switching to CCHP systems reduces the amount of input energy required by 3%, 12%, and, 20% for the multifamily, medium office and large office building, respectively (compare the first two bars for each building type in Figure 3). Moreover, there is a tradeoff in the input energy requirement when CCHP is used; more electricity is produced per unit of energy input and the building requires less electricity from the grid. This tradeoff is shown in the medium and large office buildings in Figure 3.

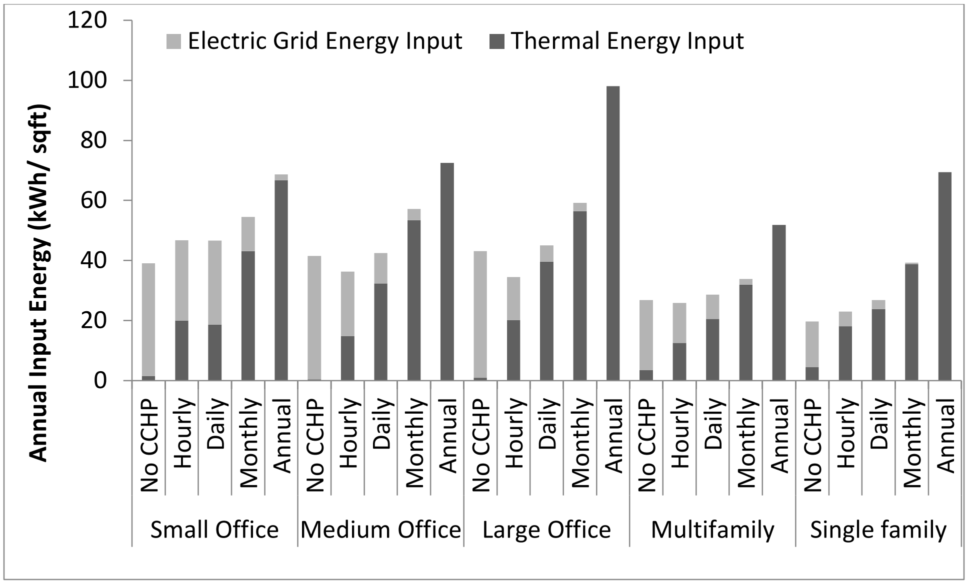

Figure 3: Input energy for all building types in all scenarios

However, for smaller buildings CCHP systems can increase energy use. The overall energy consumption increases by 53% in the case of the small office building with the system being run to meet the hourly building thermal requirements. And there is a 20% increase in the input energy (Figure 3) for the single family building complex. In these cases, even when the CCHP system was running at its lowest capacity, it was still producing more thermal energy than the building required. Figure 4 compares the scenario when the turbine operating at its lowest capacity produces more thermal energy than required by the building to that of a system which has much less excess thermal energy. In the case of Figure 4a the white space between the thermal output line and the hourly building demand is indicative of too much excess thermal energy. The increased efficiency of the CCHP system was not significant enough to offset the excess input energy required when the system was producing more thermal energy than required.

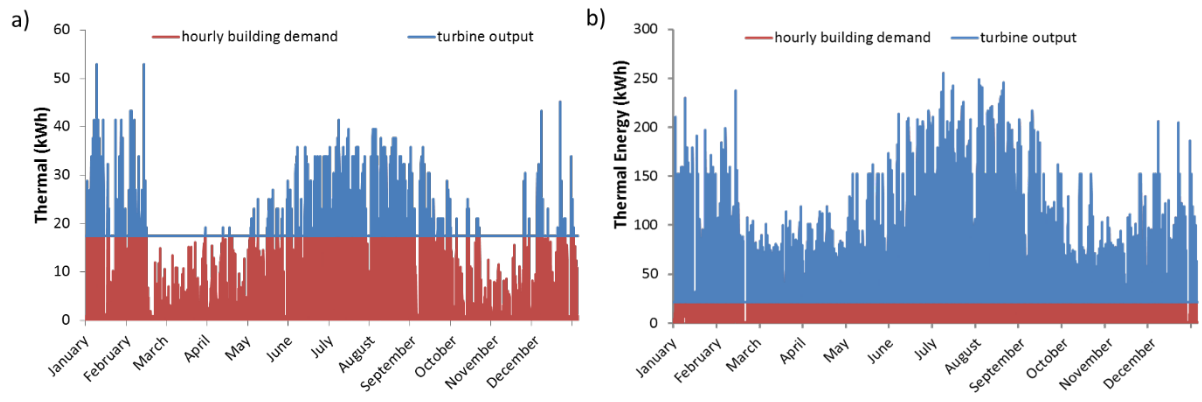

Figure 4: Building thermal demand when a CCHP system is used and the thermal output of the microturbine in the CCHP system. a) Thermal demand of a small office building (2 buildings) and the thermal output of a 30kW turbine matching the hourly thermal demand. b) Thermal demand of a medium office building and the thermal output of a 130kW turbine matching the hourly thermal demand.

Energy and 'water for energy' savings

In all scenarios, for all building types there was a significant reduction in the amount of electricity required from the grid when compared to the centralized system. Modifying the thermal demand resulted in the CCHP system running at a higher capacity for longer periods of time so the system is able to provide more electrical energy to the building. The operating scenarios that require the turbines to consistently operate at higher outputs reduce the building's dependence on the electrical grid as the turbine is able to meet most or all of the buildings electrical demand. The single family building is always able to meet the electrical load of the building and produces excess electricity that can be sold to the grid. Scenarios that require the microturbines to operate constantly to meet a higher thermal demand produces more electricity resulting in less electrical energy being required from the power grid.

Figure 5 illustrates the water consumption for energy production of a medium office building under all operating scenarios (FTL) with and without net metering if a combined cycle natural gas plant provided the additional electrical requirements of the building. The largest reduction is in the scenario where the turbine meets the maximum yearly thermal demand throughout the year. This was expected as in this scenario the CCHP is producing excess heat but generating more electricity than all other scenarios. This translated to a lower energy requirement from the grid and corresponding reduction in ‘water for energy’ consumption. The water for energy results were similar for all other buildings except the small office building. The water consumption for energy production did not diminish to zero in the case of the small office building because even operating constantly at the maximum electricity output of the CCHP system was not enough to meet the electricity demands of the building. The water for energy demand for all buildings and scenarios that have a CCHP system is less than that of the central grid scenario (See Appendix C Figure B1).

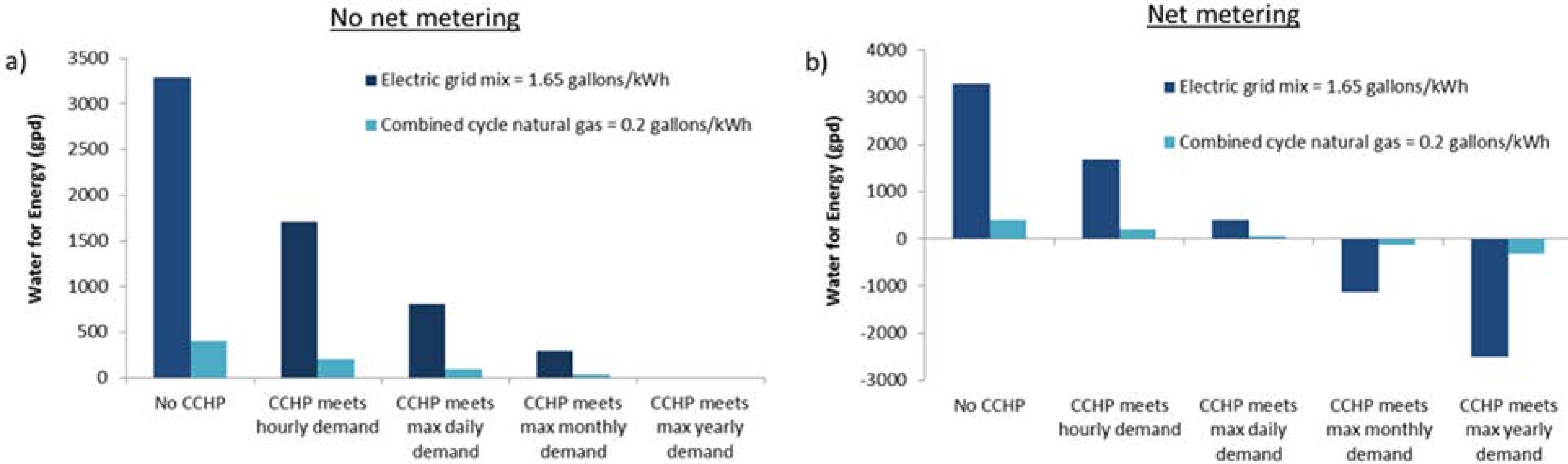

Figure 5: 'Water for energy' consumption for a medium office building comparing the consumption factor of the Georgia grid to the consumption factor of a combined cycle natural gas plant. a) Water for energy consumption of a medium office building with a CCHP system and no net metering. b) Water for energy consumption of a medium office building with a CCHP system and net metering. Negative water for energy consumption is the water consumption mitigated by the grid because it is generating less electricity.

Emissions reductions

The hourly demand operation scenario has the lowest emissions for a medium office building, and the systems can be operated to meet the maximum daily demand and still have less emissions than a no CCHP scenario (Figure 6a). However, if the system is operated at the maximum monthly or maximum annual demand, the emissions from the CCHP system are greater than the conventional system as too much heat is wasted. CO2 emissions for the medium office building were reduced by 35% when the CCHP system was operated to meet the hourly thermal demand. All buildings have the lowest CO_2 emissions when the system was run to meet the hourly thermal demand (Appendix C FigureC1 a). The single family buildings had the highest emission reduction of 38% while the small, large offices, and multifamily buildings had a decrease in emissions of 12%, 28% and 29% respectively. The multifamily building has the highest flexibility in how the CCHP system is operated and there will always be a reduction in the CO_2 footprint.

The NOx emissions will be reduced under all CCHP system operation scenarios for the medium office building (Figure 6b). The greatest reduction in NOx emissions for the medium office building is 83%, and occurs when the CCHP system is operated to meet the maximum annual thermal demand. For most buildings the NOx emissions will be reduced once a CCHP system is used, but the best case scenario for NOx reductions will depend on the operating scenario. For the single family housing case there is a 1% increase when the system is operated to constantly meet the maximum annual demand. The single family buildings will see a maximum NOx reduction of 75% when the CCHP system is operated to meet the hourly demand. The maximum NOx reduction achievable for large office and multifamily residential building is 84% and 87% respectively; if the systems are operated to constantly meet the maximum monthly thermal demand. Similar to the medium office building, the small office buildings have a maximum NOx reduction potential of 80% if the systems are operated to meet the maximum annual demand. The difference in maximum achievable NOx reduction for different building is attributable to the tradeoff between the wasted thermal energy and reduced energy demand from the grid.

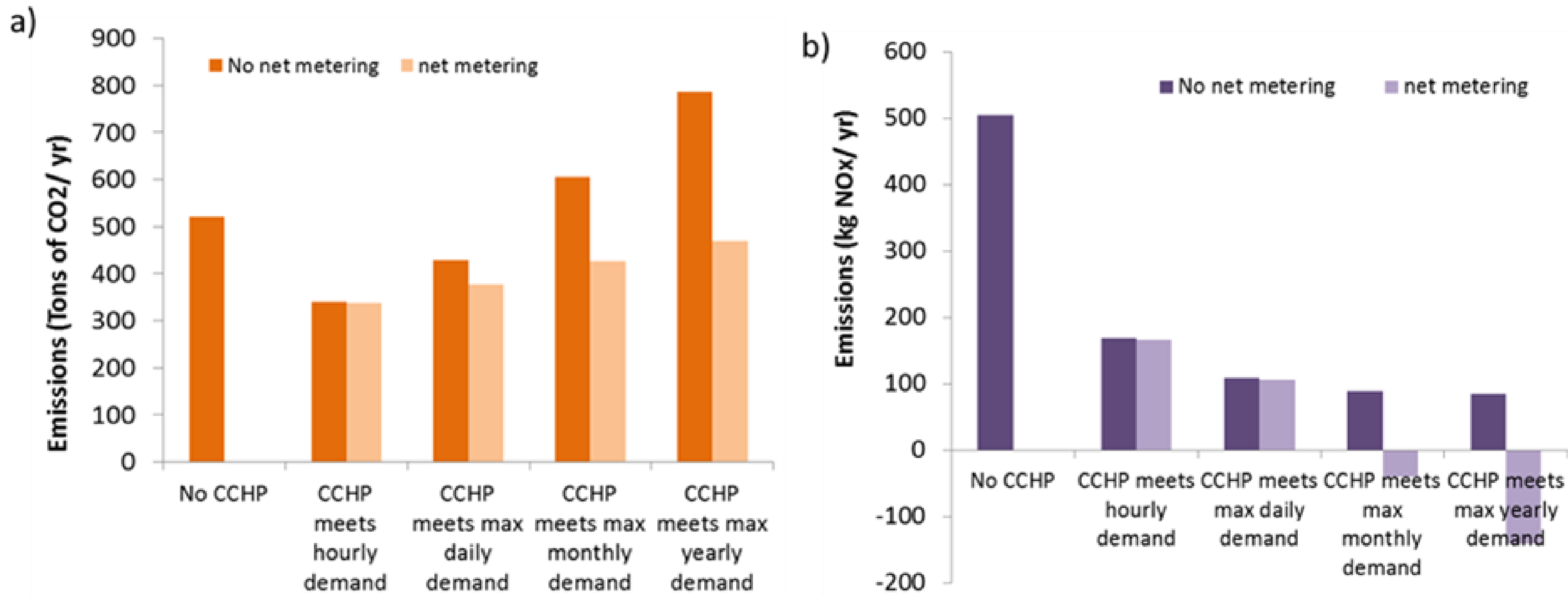

Figure 6: Annual emissions for a medium office building operating under varying CCHP operations. a) CO_2 emissions b) NOx emissions. Negative emissions is the emissions mitigated because over the year the grid is generating less electricity.

Cost

The medium office buildings is the most economical for CCHP systems operating under all 5 scenarios using the maximum and minimum expected annual cost of the system (Figure 7). The medium office building could have a cost savings of approximately 50%, if the CCHP system is operated to meet the hourly thermal demand of the building and the minimum expected cost of the CCHP system is assumed. The cost savings will decrease to 42% for the medium office building under the same operation scenario. If the price of natural gas being charged is comparable to the price faced by utilities, the cost of the system are further reduced (Figure 7). Figure 8 and Appendix F Figure F1 have the potential cost reductions for all building types and operating scenarios, assuming the maximum and minimum cost of the CCHP system. The maximum savings potential of the multifamily residential building is 29 % if the CCHP system is operated to meet the maximum daily thermal demand of the building. The small office building and the single-family residential buildings are the two building types in which a CCHP system is more expensive than not having a CCHP no matter how the system is being operated (Figure 8). The cost of the fuel is a large determining factor whether CCHP systems will be economically beneficial. The cost of fuel to the CCHP system can significantly affect the overall costs of the system. For example in the case of the medium office building (Figure 7) when the price paid for natural gas is similar to that charged to utilities the cost of all scenarios is reduced by 10%-50%. Another reason a CCHP system is not beneficial for these two buildings is the capital cost of the HVAC systems for these buildings is the lowest among all buildings. The cost of the CCHP systems could be greatly impacted by the cost of natural gas. The price of natural gas depends on the user category. If buildings with CCHP systems were charged the same price for natural gas as utilities then the cost of the fuel inputs could decrease by at least 50%, making CCHP systems more economically viable under all operating scenarios.

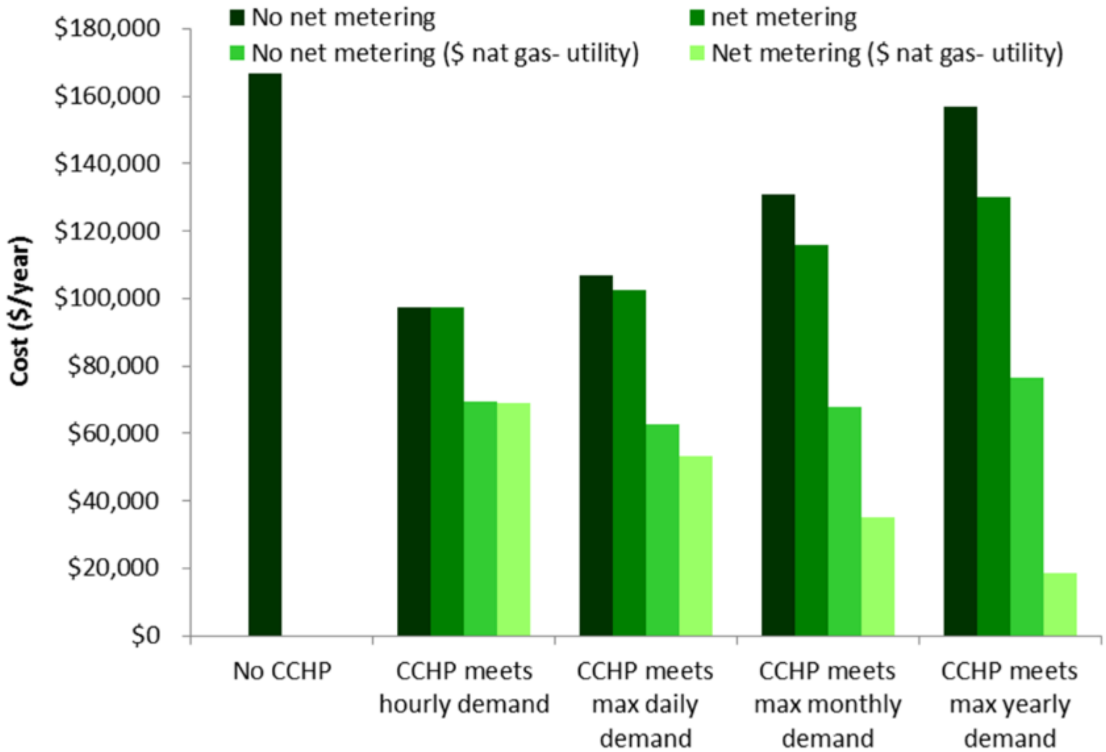

Figure 7: Cost of implementing CCHP systems operating at various capacities, with and without net metering, and comparing the residential and commercial natural gas pricing rates to that of utilities for a medium office building.

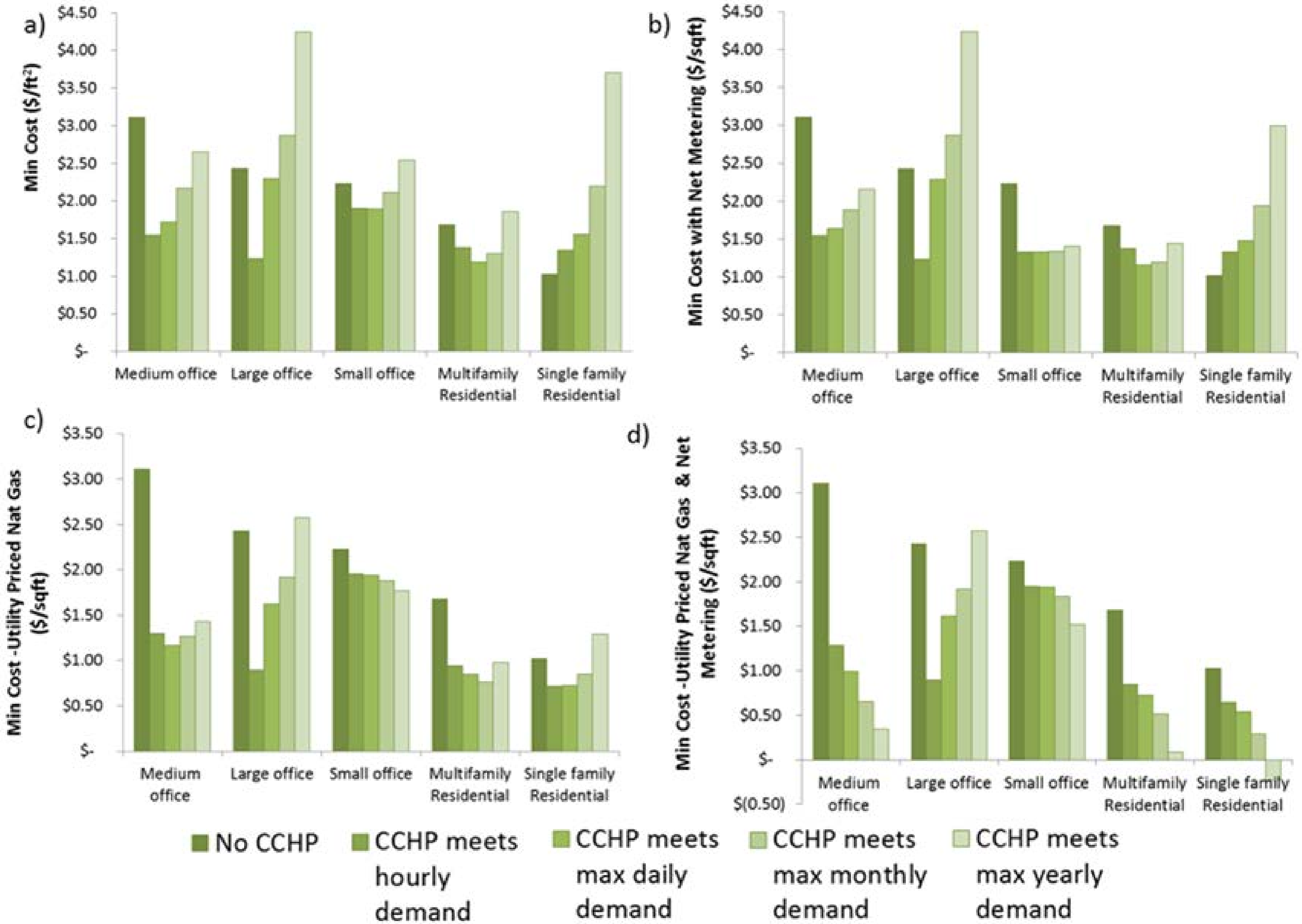

Figure 8: Per square foot cost estimates of CCHP systems compared to the cost of energy in the no CCHP scenario for all 5 building types. a) Minimum CCHP system cost estimates with no net metering. b) Minimum CCHP system cost estimates with net metering. c) Minimum CCHP system cost estimates with no net metering and assuming the price of natural gas is equal to what utilities pay. d) Minimum CCHP system cost estimates with net metering and assuming the price of natural gas is equal to what utilities pay.

Impact of net metering

Net metering can result in significant reductions in 'water for energy' consumption, CO_2 emissions, and NOx emissions of all buildings and all operating scenarios of the CCHP system. When a net metering policy is considered for the medium office building operating the CCHP system in the best 'water for energy' and NOx emissions savings (Figure 5b and Figure 6b). All building types had the highest reductions in water for energy consumption and NOx emissions when the CCHP system was operated to meet the maximum annual demand (AppendixC, Appendix E). Water for energy consumption and NOx emissions are negative in net metering scenarios because over the entire year for all operating scenarios, the net electricity required by the building is negative. This means that selling excess electricity to the grid results in the grid generating less electricity and water for energy consumption and NOx emissions are reduced.

Net metering has the greatest impact on the CO_2 emissions of the medium office building when the CCHP system was operated to meet the hourly demand of the building (Figure 6a). Operating the system with net metering to meet the hourly demand reduced the CO_2 emissions by 35%. However, the CCHP system for the medium office building can be operated to meet the maximum annual demand and still produce less CO_2 emissions than the no CCHP scenario when considering net metering. Single family residential and small office buildings also had the greatest reduction in CO_2 emissions when the CCHP system is operated to meet the hourly thermal demand of the building. Operating the CCHP system to meet the hourly thermal demand of the building and using net metering resulted in a 12% and 45% reduction in CO_2 emissions for the small office and single family buildings, respectively. The large office and multifamily buildings had the greatest CO_2 emissions reductions when the system was had net metering and was operated to meet the annual max thermal demand of the buildings. The CO2 reductions for the large office and multifamily buildings were 59% and 33%, respectively (AppendixC Figure 38).

The cost savings increase when net metering is used with the CCHP system. The annual costs of medium office, large office, and multifamily buildings can be reduced by 42%, 45%, and 9%, respectively, when the maximum cost of the CCHP system is used. Using the minimum annual costs of the system the medium office, large office, and multifamily buildings can be reduced by 50%, 49%, and 18%, respectively. For these three buildings the maximum cost reduction occurs when the CCHP system is operated to meet the hourly thermal demand of the building. The small office and single-family buildings do not see a reduction in costs even when net metering is considered. If the cost of natural gas charged to the system was comparable to the price face by utilities the annual costs can be reduced to 10%- 30% of the No CCHP costs. In the case of the single family homes, net metering and utility priced natural gas result negative system costs (Figure 8d). This means that the system can make the owners money as opposed to costing them.

In all buildings, except the small office building, there is negative ‘water for energy’. This is because the excess energy produced by the CCHP system is sent to the grid so the energy grid needs to produce less electricity resulting in avoided “water for energy” consumption for all buildings. In the case of the small office building, on an annual basis the CCHP system sells less electricity to the grid than it buys. This is the main reason there is no negative water for energy savings. In all cases, increasing the operational capacity of the turbine consistently results in lower ‘water for energy’ consumption.

CHAPTER 3

ESTIMATING THE POTENTIAL IMPACT OF CCHP ON TWO URBAN GROWTH SCENARIOS: A CASE STUDY OF ATLANTA

Urban areas are the key to improving energy efficiency and decreasing the environmental impacts of energy production. Understanding how wide-scale implementation of decentralized CCHP systems will impact the emissions and water consumption for energy production can inform leaders and policy makers on the potential of these systems. The objective of this section is to estimate: 1) the environmental impacts of large-scale implementation of CCHP systems compared to conventional energy systems; 2) the effect a net metering policy can have on region-wide emissions and "water for energy" consumption; 3) how and if urban growth policy impacts the feasibility of CCHP systems.

Methodology

The estimation of the impact CCHP can have on two urban growth scenarios is based on work done in 'What if' by Marty Sung and Dr. Steve French. Data is from between 2005 and 2030 under two growth scenarios. 'What if?' is a land use support tool that was used to predict the future land-use patterns of the 13-county Atlanta Metropolitan region(Figure 9)[72]. 'What If?' uses the population and employment growth estimates developed by the Atlanta Regional Commission (ARC) and twelve socioeconomic and morphological geospatially distributed attributes to allocate future development locations. The twelve attributes were: distance from major roads, distance from floodplains, distance to parks, distance to highway ramps, distance to rail, distance to town centers, distance from lakes and rivers, distance to negative facilities (such as landfills), existing industry, city boundaries, public land and national parks, and slope of the land. These attributes were used to predict two growth patterns: business as usual (BAU) and more compact development (MCG). The BAU and MCD scenarios had four major differences. The MCG scenario: (1) restricted growth to areas close to preexisting transportation corridors, (2) had a 50% to ~100% increase in residential and employment density over the BAU scenario, (3) had a 17% increase in the number of multi-family housing units allocated for the future residential use, and (4) assumed higher infill rates in land demand analysis. The results from the tool were estimates of the total number of single family and multifamily residential housing units (HU) required and the total square footage of commercial space.

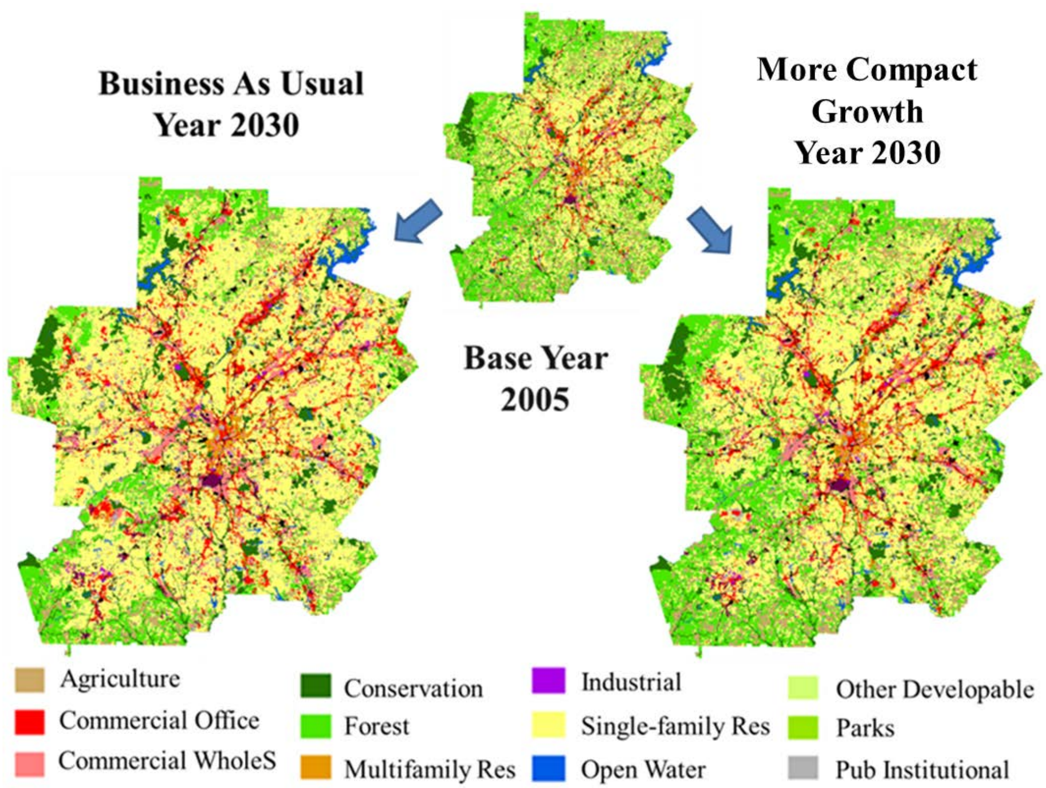

Figure 9. Land use/land cover changes from 2005 to 2030 for both BAU and MCG scenarios.

Using estimates from the smarttraq database we estimated the percent of the total commercial building square footage that fell into the category of small, medium and large office building. The range for small office building was anything less than 10,000 square feet and large office buildings were considered to be anything greater than 100,000 square feet. Medium office buildings were classified as any building between these two ranges. We determined, in 2005, the percent of the total square footage that fell into each category for all the 13 counties (Table 4). The calculated percentages were applied to the 5-year 'What if?' growth increment for each county to determine the square footage to be applied to each building type. We used data from Chapter 2 to determine the change in emissions (CO_2 and NOx), and water consumption for energy production for all office buildings with and without a CCHP system between 2005 and 2030.

In the case of the Multifamily residential building the number of housing units estimated was translated to total square feet by multiplying the number of housing units by the average size of a unit in the South[73]. Using the total square footage growth in each scenario along with the per square foot estimates for emissions and water consumption (Figure 38Figure 39), we were able to estimate the change in emissions and water consumption with and without a CCHP system.

The sizing of the residential CCHP systems was determined using the 5 year growth outputs of the 'What if?' model and the number of new housing units that would be needed for each census tract. It was assumed that all new buildings in each growth period would be a new community that would have one or more CCHP system. A matlab model was designed to determine the maximum CCHP system size that would be needed for a new community based on the maximum hourly thermal load of the community.

Since the CCHP system is composed of multiple microturbine units, a large community can have multiple smaller units placed throughout the community. Therefore, even though the matlab model determines the overall CCHP system size for a community it does not need to be a centralized but can be split into smaller units throughout the community. The emissions (CO_2 and NO_x) produced and water consumption demand for energy generation were determined for each community. This was based on estimates of the emissions and water consumption for electricity demanded from the grid and the emissions from the CCHP system. The assumption for the emissions and water consumption with and without a CCHP system are detailed in Table 2.

The total CO_2 emissions, NO_X emissions, and water consumption for energy production for the growth in the residential and commercial building in the 13 county Atlanta Metropolitan region under all four scenarios (BAU with and without CCHP and MCG with and without CCHP) was determined. We also considered the impact a net metering policy in which all excess electricity produced by the CCHP system would be sent to and used by the electric grid. The water withdrawn for electricity generation was calculated using Georgia Power estimates of the 10% consumptive water loss of all water withdrawn[74].

A best case scenario which estimated the impact of retrofitting all commercial and residential buildings and assumed that all grid energy came from a combined cycle natural gas plant (CCNG) was added to the study. The scenario assumed that all buildings prior to 2005 would fit the 5 building prototypes previously discussed. The total emissions and water consumption based on the retrofit was determined using the total estimated square footage of all the office buildings and multifamily buildings in 2005 along with the emissions and water consumption estimates in chapter 2**.**. We used estimates for the emissions and water consumption for single family residential buildings from chapter 2.

Results and Discussion

Table 4 lists the percentage of each building types applied to the growth projections. In general, across all counties the medium office building has the highest percentage of the total square feet. The two exceptions to this are DeKalb and Henry County.

Table 4: Ratio of the percentage of various office buildings

% smarttraq total commercial office space	small office	medium office	large office
Cherokee	35.2%	49.0%	15.8%
Clayton	34.8%	51.3%	13.9%
Cobb	12.0%	49.6%	38.3%
Coweta	30.9%	55.7%	13.4%
DeKalb	26.9%	30.8%	42.3%
Douglas	32.0%	50.1%	17.8%
Fayette	30.9%	40.8%	28.3%
Forsyth	32.8%	51.6%	15.6%
Fulton	21.2%	42.0%	36.9%
Gwinnet	19.1%	47.0%	33.9%
Henry	7.6%	24.9%	67.5%
Paulding	44.3%	47.3%	8.4%
Rockdale	18.0%	50.6%	31.4%
total 13 county	19.1%	42.8%	38.1%

In all scenarios incorporating a CCHP system can reduce the water consumption for energy production, NOx emissions and CO2 emissions. Adding a CCHP system to the BAU scenario will reduce the water consumption for energy production by approximately 82% without net metering, and by 90% with ne metering (Figure 10). In the MCG scenarios the “water for energy” reduction is 70% and 75% without and with net metering respectively. The percentage reductions are similar if the energy from the grid is all assumed to come from a combined cycle natural gas plant.

The CO_2 emissions can be reduced up to 23% between 2005 and 2030 when comparing the BAU CCHP versus no CCHP scenario (Figure 11). With a net metering policy, the CO_2 emissions can be reduced by 37%. When the MCG scenario is considered the reductions are 25% and 31% without and with net metering. Similar reductions are seen if it is assumed that all the energy coming from the grid is provided by a combined cycle natural gas plant. The NOx emissions will be reduced by approximately 70% in the BAU without net metering scenario and 80% with the net metering scenario (Figure 12). In the MCG scenario the NOx emissions will be reduced by 63% without net metering and 70% with net metering.

It is interesting to note that between simulations that assume electricity from the grid comes from the grid mix versus a combined cycle natural gas plant, there is no real reduction in the CO_2 and NO_x emissions. However, the water consumption for energy production when using a CCNG plant is only 12% of the water consumption from the grid mix. This can have interesting policy implications because there has been a push to convert coal-fired power plants to natural gas. Switching to CCHP systems would actually result in a greater decrease in CO_2 emissions than switching to CCNG power plants. Switching to CCNG plants would, however, reduce the NO_X emissions by approximately 20%. The biggest gains in switching to a CCNG plant are in the reduction of water consumption, an estimated 90%.

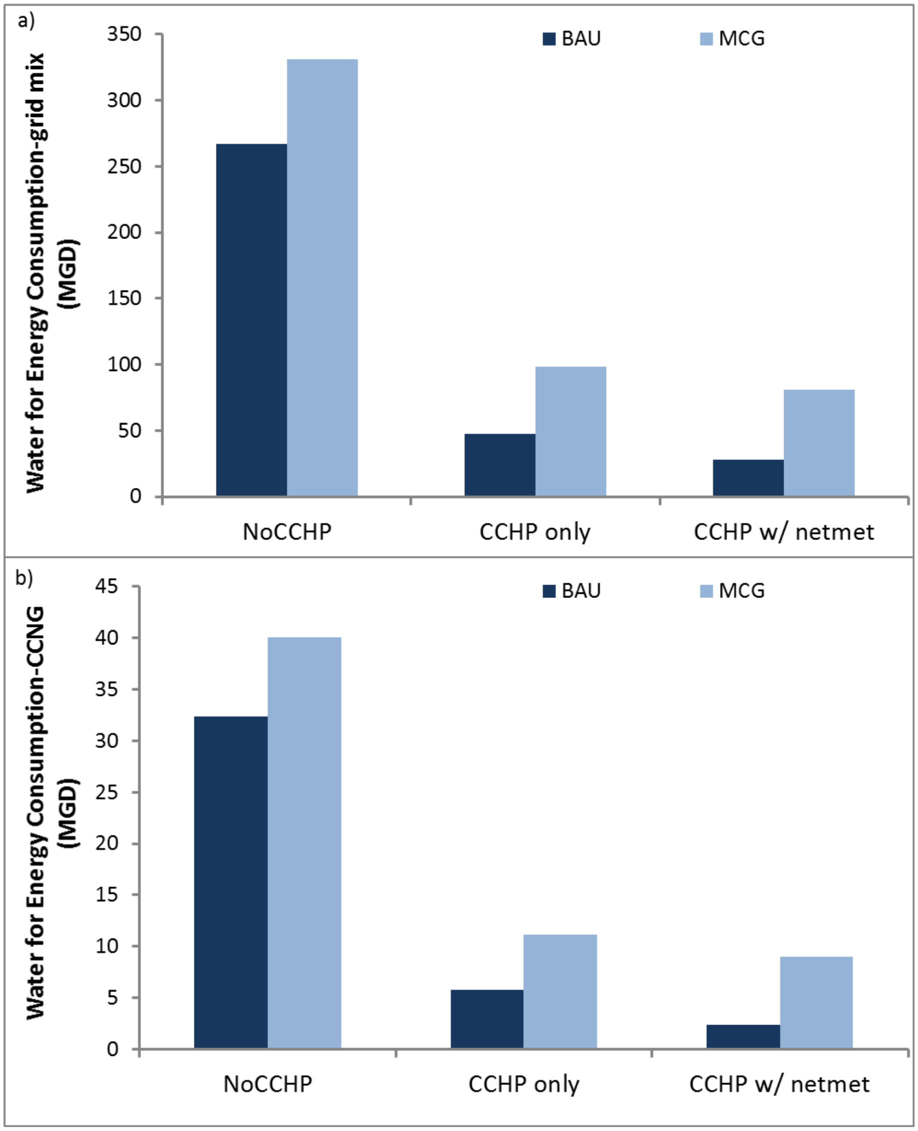

Figure 10: Water consumption for energy generation projections (2005-2030) for two growth scenarios in the 13-county Atlanta metropolitan region. a) "Water for energy" projections assuming grid mix water consumption factor. b) "Water for energy" projection assuming CCNG consumption factor.

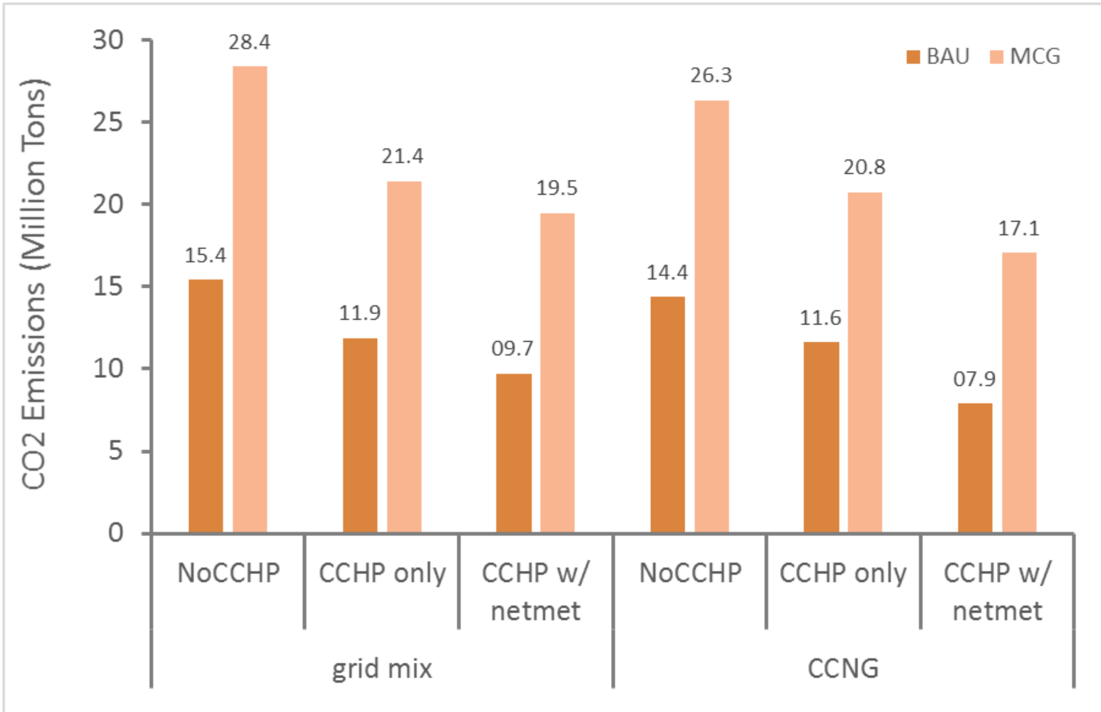

Figure 11: CO_2 emissions from energy consumption commercial and residential buildings for two growth scenarios, between 2005 and 2030.

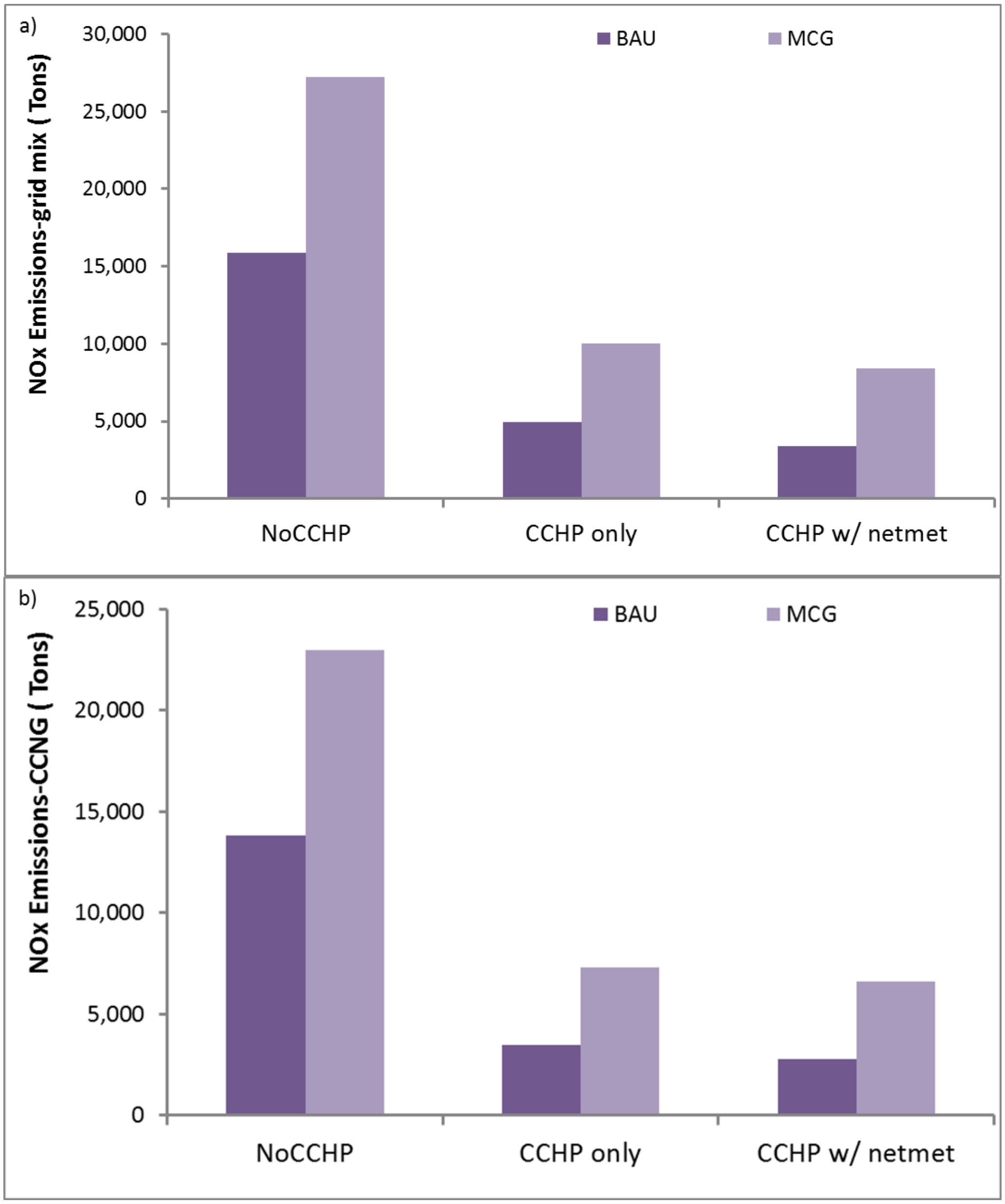

Figure 12: Projected NO_X emissions between 2005 and 2030 for commercial and residential growth in the 13 county Atlanta metropolitan region. a) NO_X emissions assuming grid-mix emissions factors. B) NO_X emissions assuming CCNG emissions factor.

The results are higher in the MCG scenario than in the BAU scenario because the total number of housing units increases between scenarios. The overall population remained the same between the BAU and MCG scenarios but multifamily units have a lower occupancy than single-family units. Therefore, a scenario such as MCG which emphasizes an increase in the ratio of multifamily units to single-family units would require more housing units overall. In this study for the 13-county Atlanta Metropolitan region approximately 815 additional units will be required in the MCG scenario than in the BAU scenario. The increase in the number of apartment units alone does not account for the approximate 30% increase in the emissions and water consumption between the BAU and MCG scenario in the no CCHP case. Figure 13 is an estimate of the number of people per square foot in each housing type, adapted from the American Community Survey data of the total population in different housing unit types, the number of units in a structure, and estimates of the square footage of each structure[75, 76]. The greater the number of people per square foot the higher the energy per square foot, and therefore the higher energy consumption. Figure 14 shows the approximate electricity demand per person by county and the housing unit type. In this case, there are four instances in which the energy per person in the multifamily residences is less than in Single-family residences. In order for the energy per person in a multifamily unit to equal that of someone living in a single family unit the size of the household in multifamily units would need to increase by approximately 20% in all counties. It would only be beneficial to increase the number of multifamily units in these counties. Solely increasing the ratio of multifamily housing units will not be as impactful with regards to reducing energy consumption. Either increasing the occupancy (number of people per housing unit) of the multifamily units or decreasing the size of the units will be more impactful in terms of energy reduction.

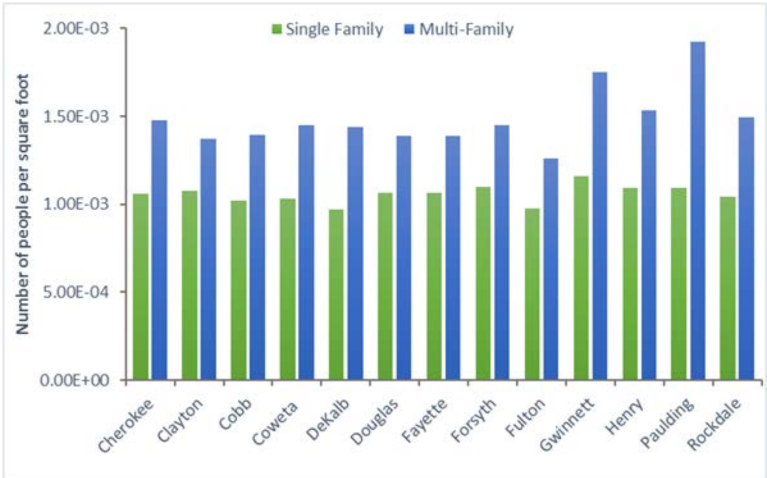

Figure 13: Number of people per square foot for two building types (Single Family and Multi Family) for the 13 county Atlanta Metropolitan region.

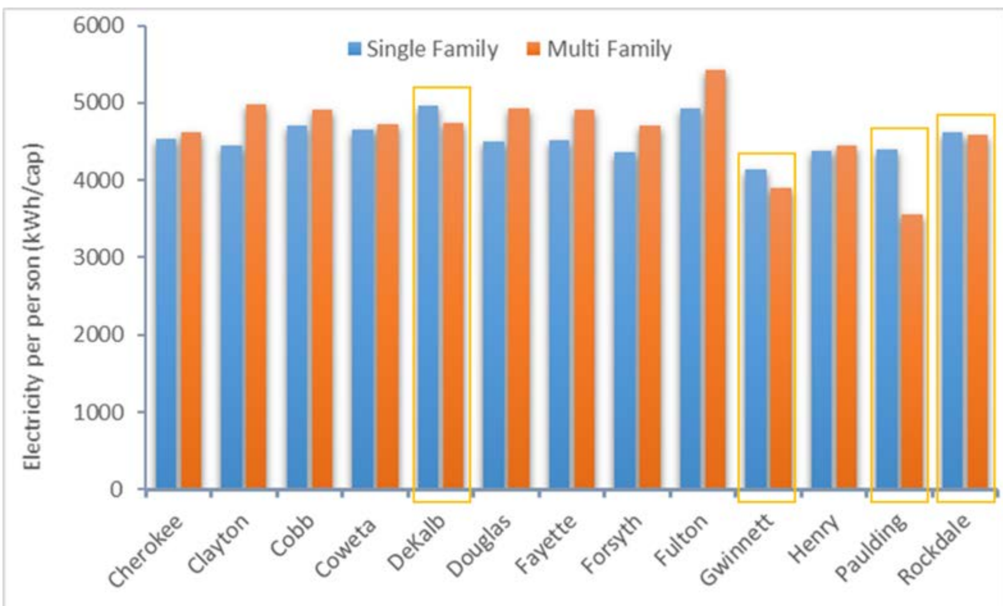

Figure 14: Electricity demand per person for two building types (Single Family and Multi Family) for the 13 county Atlanta Metropolitan region.

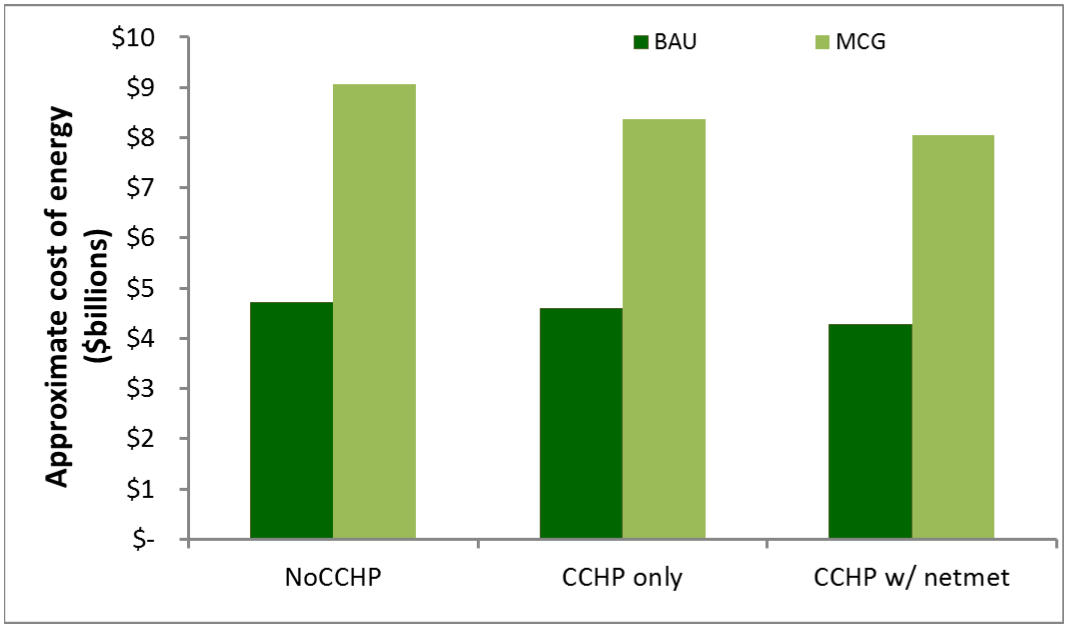

Figure 15: Cost of energy generation (includes the cost of energy required from the grid, cost of the CCHP systems, and cost of the HVAC system) for the BAU and MCG scenario.

Retrofitting all residential and commercial buildings would reduce the CO_2 emissions, from energy generation, by 58% (without net metering) and 63% (with net metering) in the BAU scenario assuming the grid mix of technologies when compared to the no CCHP case(Figure 16). The CO2 reductions in the MCG scenario, compared to the no CCHP case, are 52% without net metering and 56% with net metering. If we assume that all future grid technologies will be CCNG plants then without CCHP systems the CO_2 emissions would be reduced by 46% and 40% in the BAU and MCG scenarios respectively. If we compound this by adding in CCHP systems to a CCNG grid system then the potential CO_2 reductions in the 13-county area would be 60% in the BAU and 53% in the MCG scenarios (Figure 16).

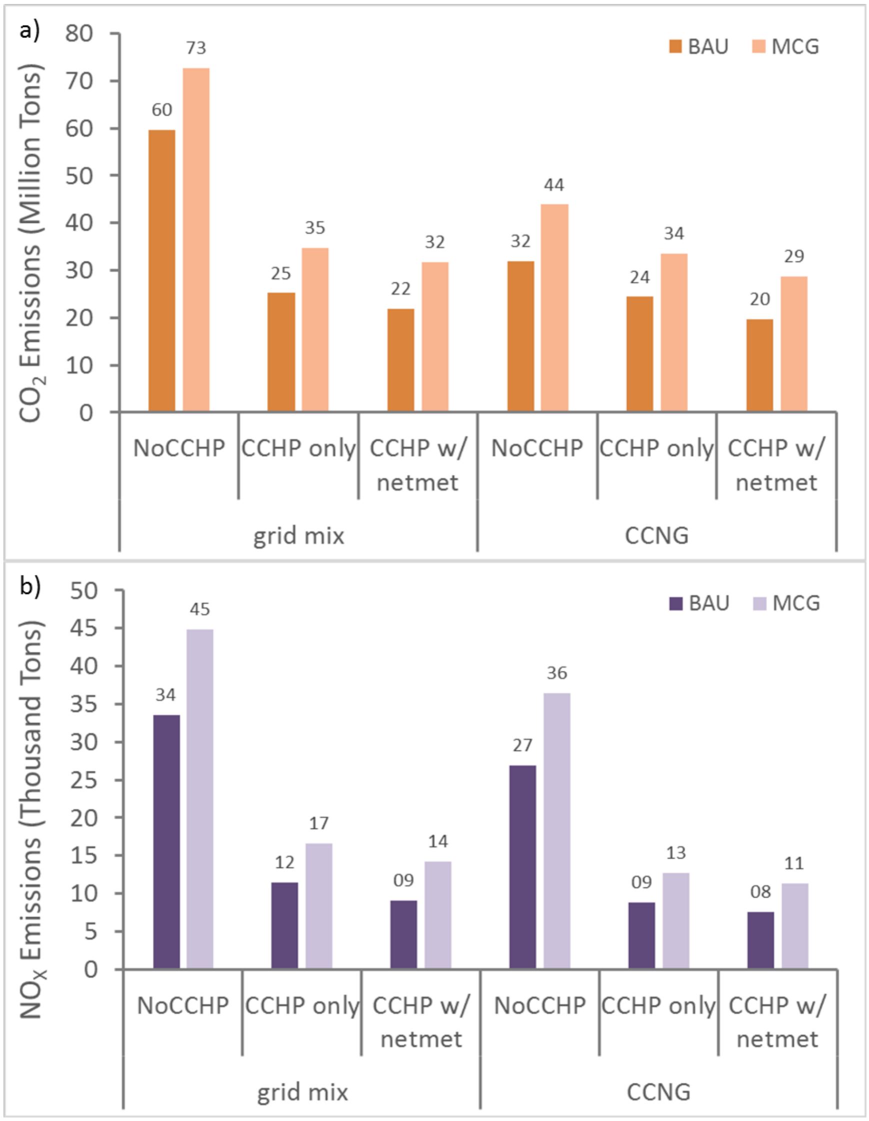

Figure 16: Total emissions of the 13-county Atlanta Metropolitan region, from energy consumption commercial and residential buildings for two growth scenarios if all buildings in the base year are retrofitted with CCHP systems. a) CO_2 emissions. b) NOx emissions.

CHAPTER 4

IMPLEMENTING SOLAR PV WITH CCHP SYSTEMS AND THE POTENTIAL POLICY REQUIREMENTS TO INCREASE THE FEASIBILITY OF THESE SYSTEMS

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Typically, Hybrid PV-CCHP systems have been studied such that the CCHP system is used as a backup for intermittent PV generation. We would like to understand factors that determine what the optimum size of the PV portion of a hybrid PV-CCHP system should be and the economic viability of such a system[77]. Figure 17 describes the new proposed system in which PV is added to the CCHP system. In the PV-only system, PV in combination with the grid system, the thermal demand of the building (space heating and hot water) is supplied by a furnace or boiler and the electrical energy required for the plug load and space cooling comes from PV and the utility power grid. The energy demands in the hybrid PV-CCHP system differed from the PV-only systems as the thermal load, which includes the space heating, space cooling, and hot water demands of the building, is supplied by CCHP and the plug load is met with PV, CCHP and the utility grid (Waste heat from the microturbine supplies space heating and hot water, and space cooling is obtained by sending the heat generated by the microturbine through an absorption chiller). The objective of this section is to determine what the optimum PV sizing, with and without a CCHP system, would be for 5 building typologies located in the Atlanta Metropolitan region. We also assess the implication of four policies on determining the optimum sizing. The policies are a carbon tax, avoided damage costs for mitigating NO_x emissions, feed-in-tariffs (F.I.T.), and credits for reducing the water consumption for energy generation.

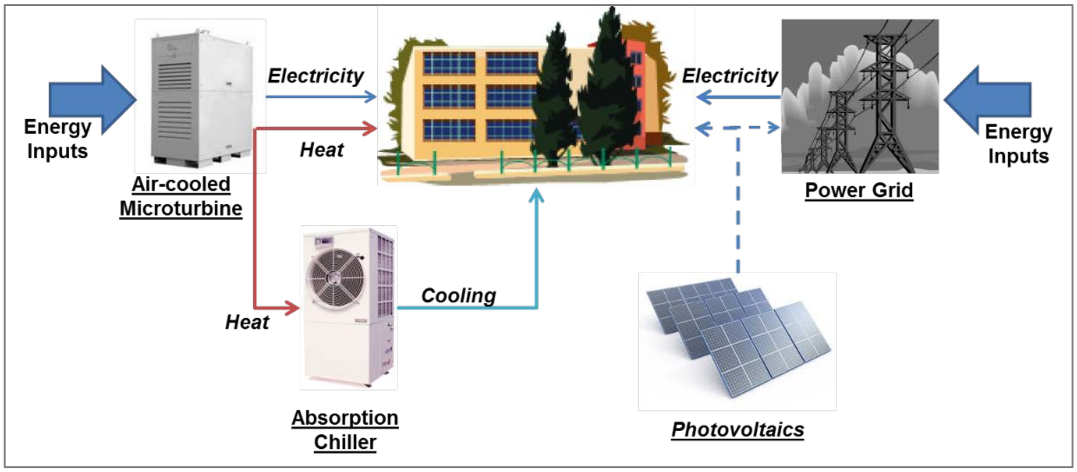


Figure 17: Proposed hybrid PV-CCHP system.

Methodology

PV System Design

The PV system was designed using monocrystalline silicone PV modules mounted a 30 degree angle towards the south and a peak power factor of 0.15 kW/m^2 [78]. We used the Energy Performance Standard Calculation Toolkit (EPST), developed by the High Performance Building group at Georgia Tech, to obtain the hourly output of the PV panels [79]. The toolkit uses TMY3 weather files for the Atlanta region to determine the solar irradiance for the region and the hourly electrical output of the PV system is calculated using the efficiency of the PV panels, tilt, orientation and surface area of the panels.

The minimum required distance between PV arrays was calculated using a separation factor of 2 from the NABCEP PV resource guide[80]. The separation factor is the ratio of the minimum distance between a row of PV panels and the height of the panels [80]. For the single-family residential building we assume that only half the roof is available for PV and that the building is oriented southward. Equation 9 determines the total PV area that can be used for a given building. The PV surface area factor is the ratio of the area of the PV as compared to a building's useable roof area. Using the EPST toolkit we estimated the amount of electricity generated for various PV system sizes based on the percent coverage of the PV on the useable roof area. The maximum useable roofing area for the PV is 80% of the total roof area.

$PV\ Area = PV\ surface\ aea\ factor * useable\ roof\ area$ (9)

The avoided electricity is the energy produced by the PV system that is used by the building. It is the energy that no longer needs to be generated by the electrical grid. If the electricity generated by the PV system is greater than the demand of the building this electricity is sent to the grid.

In this section we took two steps to examine the feasibility of PV-only systems in the Atlanta metropolitan region as well as their feasibility when used in conjunction with CCHP systems.

The minimum required distance between PV arrays was calculated using a separation factor of 2 from the NABCEP PV resource guide[80]. The separation factor is the ratio of the distance between the PV panels and the height of the panel[80]. For the single-family residential buildings we assume that we only have of the roof is available for PV and that the building is oriented southward. Equations 10 and 11 determines the total PV area that can be used for a given building. Using the EPST toolkit we estimated the amount of electricity generated for various PV system sizes based on the percent coverage of the PV on the useable roof area.

$PV\ surface\ area\ factor = \frac{2}{\sqrt{3}+separation\ factor}$ (10)

$PV\ Area = PV\ surface\ aea\ factor * useable\ roof\ area$ (11)

Benefit Cost Analysis of the PV-only system

The net present value (NPV) of installing various sized PV systems for each building type was calculated by finding the difference between the present value of the benefits and the cost of implementing the system. In this study the benefits considered are: 1) The avoided electricity, 2) Feed-in tariffs for the electricity that is overproduced, 3) Carbon tax savings, 4) water consumption credits, and 5) Avoided damage cost due to air quality improvement. The annual benefits were calculated using equations 12 to 20. The costs are the PV module and balance of system costs.

The annual savings from avoided grid electricity production is the energy produced by the PV system that is used by the building times the price of electricity (equation12). The savings from a feed-in tariff is the excess energy produced by the PV system that can be sold to the grid (equation13). The impacts of various feed-in tariff rates were varied to determine the minimum feed-in tariff to make the PV system feasible. The rates used increased by 1¢ increments from 0¢/kWh (no FiT) to the full price of electricity, 10.44¢/kWh and 12.55¢/kWh for commercial and residential buildings, respectively [62]. The total avoided electricity benefits and feed-in tariffs for a building was calculated using a discount rate of 0% and 5% over the 25-year lifetime of the PV system [81].

$Avoided\ Elec\ Cost_{PV} = Price_{elec} * electricity_{used\ by\ building}$ (12)

$electricity_{overproduced} = electricity_{generated\_PV} - electricity_{used\ by\ building}$ (13)

$Annual\ F.I.T. = rate_{feed\ in} * electricity_{overproduced\ (PV)}$ (14)

The cost of the PV system was estimated from the cost of the panels and the balance of system (BOS). The BOS include the mounting frame, inverter, monitoring system, feed-in meter and DC/AC cabling. The Balance of cost (BOS) was assumed to be $1.85/Watt [82] and the panel cost was assumed to be $1.1/Watt. We determined the Cost per square meter of the PV system using the cost per watt along with the peak power factor. We assumed that there are no O&M costs associated with the PV system [83]. Additionally, we estimated the NPV of the system if the cost of solar were to fall to $1/Watt [84]. Equation 15 describes how the NPV of the PV system without any policy implications while equation 16 includes energy policy such as a feed-in tariff.

$$NPV \;=\; Avoided\ Elec\ Cost \;\; - Cost\ of\ PV_{\%\, useable\, roof\, area\, coverage} \quad (15)$$

$$NPV \;=\; Avoided\ Elec\ Cost \;\; + F.I.T. - Cost\ of\ PV_{\%\, useable\, roof\, area\, coverage} \quad (16)$$

Carbon Tax and Water Consumption Policy

We also considered the impact 3 potential environmental policies can have on the feasibility of the system. The “water for energy” consumption policy attempts to put a price on the water consumed for energy generation. In this study, a credit is applied to the consumers for mitigating the utilities water for energy consumption. In Georgia the water consumed for energy generation is approximately 1.65 gallons/ kWh [63]. Therefore, the water saved can be calculated based on the amount of electricity that is no longer generated by the electrical grid. We assume that the credit gained is similar to the price paid by consumers to use water for irrigation purposes. The credit assumed is $0.006/gallon of water consumed, based on the irrigation numbers for Fulton County (equation 15). The damage costs are the cost due to the external effects of the NO_x of emissions produced by the energy generation process and were determined by valuing the damage to ecosystems, health impacts and loss of life due to emissions from energy generation [85]. The damage costs estimated were taken from a survey of literature published on the externalities posed by a given pollutant and ranged from $1.05/kg to $10.03/kg [85]. In this study the median damage costs of $7.92/kg was assumed [85]. The NO_x and CO_2 emissions saved were estimated based on the energy saved and emissions factors for the Georgia grid mix. The emissions factor for the Georgia grid-mix are 0.408g/kWh and 0.57 kg/kWh for NO_x and CO_2 respectively [61, 62]. The carbon tax estimates were obtained from the National Institute of Standards and Technology's (NIST) adjusted EIA potential carbon pricing numbers which varied from 2¢/kg to 7¢/kg over a 25 year period (appendix J) [86]. The carbon tax savings were calculated for estimated price each year and then adjusted to the present value. The present value of the CO_2 savings was then summed for the estimated lifespan of the system 25 year. Equations 15 – 19 show how the three environmental policies were monetized. The total NPV with all policies considered was calculated using equation 18.

$$Water\ for\ energy_{Annual\ Credit} = rate_{w4e\ credit} * electricity_{generated\ (PV)} * Georgia\ Water\ Consumption\ Factor_{grid} \quad (15)$$

$$NOx_{Annual\ saved\ damage\ costs} = Damage\ cost * electricity_{generated\ (PV)} * Emissions\ Factor_{NOx} \quad (16)$$

$$CO_{2\ saved\ CO2\ tax} = Carbon\ Tax * electricity_{generated\ (PV)} * Emissions\ Factor_{CO2} \quad (17)$$

$$NPV_{CO2+wtr+NOx} = Avoided\ Elec\ Cost_{10} - Marginal\ Cost_{PV} + F.i.T. + Carbon\ Tax_{Savings} + Water\ for\ energy_{Credit} + NOx_{saved\ damage\ costs} \quad (18)$$

PV-CCHP hybrid system

The hybrid PV-CCHP system is composed of an air-cooled microturbine, absorption chiller, and the PV system described previously. In our hybrid PV-CCHP scenario we assume that the CCHP system is operated to follow the hourly thermal load (FTL) of the building. In this scenario the thermal load is the energy required for space heating, space cooling and hot water. The electricity produced by the CCHP system and the PV system is used to meet the plug load of the building. In this scenario the avoided electricity is the electricity that no longer needs to be pulled from the grid as the PV-CCHP system is generating electricity and meeting the space cooling needs of the building. The benefits from energy produced by the turbine are also accounted for in the water consumption, CO_2 emissions and NO_x emissions reductions. An additional benefit is the avoided costs from no longer needing to purchase a heating and cooling unit (Table 1). The total cost of the hybrid PV-CCHP system includes the capital, maintenance and fuel cost of the CCHP system and the PV B.O.S. and module costs. Since the technologies in the hybrid system have different lifetimes we calculated the annual benefits and the annual costs. The annual cost of the PV system was calculated using a discount rate of 5% over the 25-year lifespan and the annual benefits from the avoided HVAC costs were calculated over a 15-year lifespan of the system. This cost plus the cost of the CCHP system is the total annual costs. The annual benefits are calculated using equations 12 to 19 but in this scenario the electricity used by the building and the over produced electricity are based on the electrical output of both the PV and microturbine. The annual net value is calculated using equation 19.

$$Annual\ Net\ Value_{CO2+wtr+NOx} = Avoided\ Elec\ Cost_{\text{Annual}} + F.I.T. - Annualized\ Cost_{PV} + Carbon\ Tax_{Annual\ Savings} + Water\ for\ energy_{Annual\ Credit} + NOx_{Annual\ saved\ damage\ costs} + Avoided\ HVAC\ cost_{\text{Annual}} - Annual\ Cost_{CCHP+fuel} \quad (19)$$

Results and discussion

The feasibility of implementing PV systems, alone or in conjunction with a CCHP system, is very dependent on the cost of the system assumed, the rate of feed-in-tariff assumed, and the existence of policies to monetize the impact of the emissions “water for energy” consumption.

PV only

The energy produced by the PV system that is used by the building is the energy avoided from the grid. Figure 18 represents the energy generated from the PV that is used by each building type depending on the area of PV coverage. Figure 18a shows that in some instances as the percent of PV coverage increases the grid energy used by the building decreases. This indicates the maximum PV size in which all the energy generated was used by the building. In the case of the large office building, the slope is almost flat therefore the building uses most of the energy generated. For the multifamily residential building, a PV area greater than 40% of the useable roof area means excess electricity that is not used by the building. This is the same for the medium office building at 20% of the useable roof area and the single-family residential building at 10% PV coverage of the useable roof area.

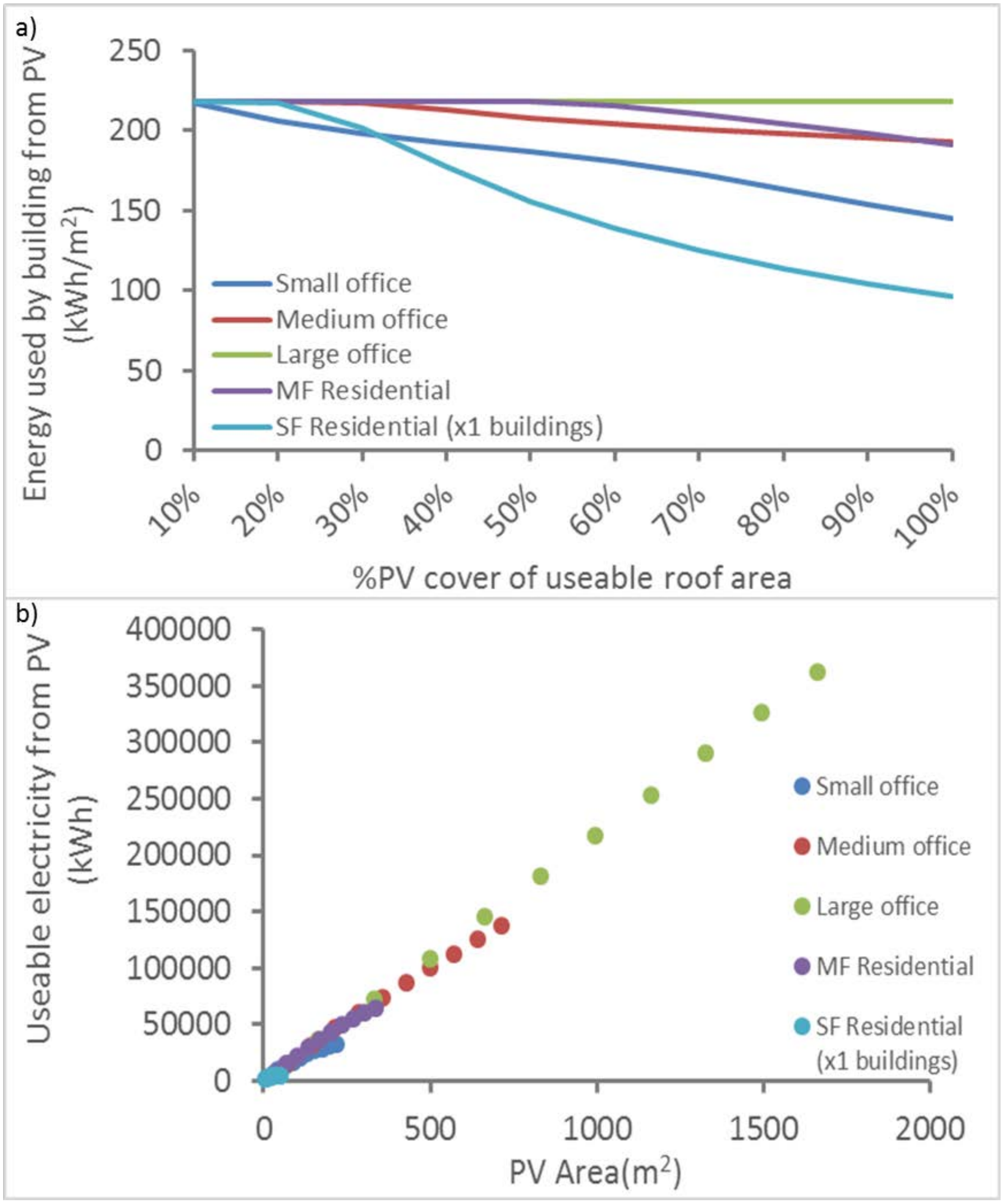


Figure 18: Annual electricity used by building from PV by each building type. a) Electricity used from PV by building per square meter of PV installed. b) Electricity used from the PV by 5 prototype buildings and the area of the PV system.

Without F.I.T., PV is not economically feasible at the current system cost. In the case of the small office building if there is no discount rate then depending on the feed-in-tariff an optimum PV size can be found (Figure 19a). In this case the lower the F.I.T. the lower the PV area that should be installed but, when the F.I.T. is greater than 8 cents per kWh then the benefits are such that you should implement the maximum amount of PV possible. When a 5% discount rate is used, there is no optimum PV size as financially because it does not make sense to employ a PV system as you never reach a breakeven point. In fact, the larger the PV system the greater the financial loss (Figure 19b). When the estimated future cost of the PV system, $1 per kW, is used an optimum PV size can be found depending on the F.I.T. and the amount of PV installed. At a certain F.I.T. the maximum amount of PV should be implemented as the difference between the marginal benefits and the marginal costs are positive until the largest PV area is implemented. In the case of a 0% discount rate and the future cost of $1/ Watt you should implement the maximum amount of PV no matter the F.I.T. (Figure 19c). Accounting for a 5% discount rate means that for F.I.T.'s below 2 cents per kWh an optimum PV size can be found.

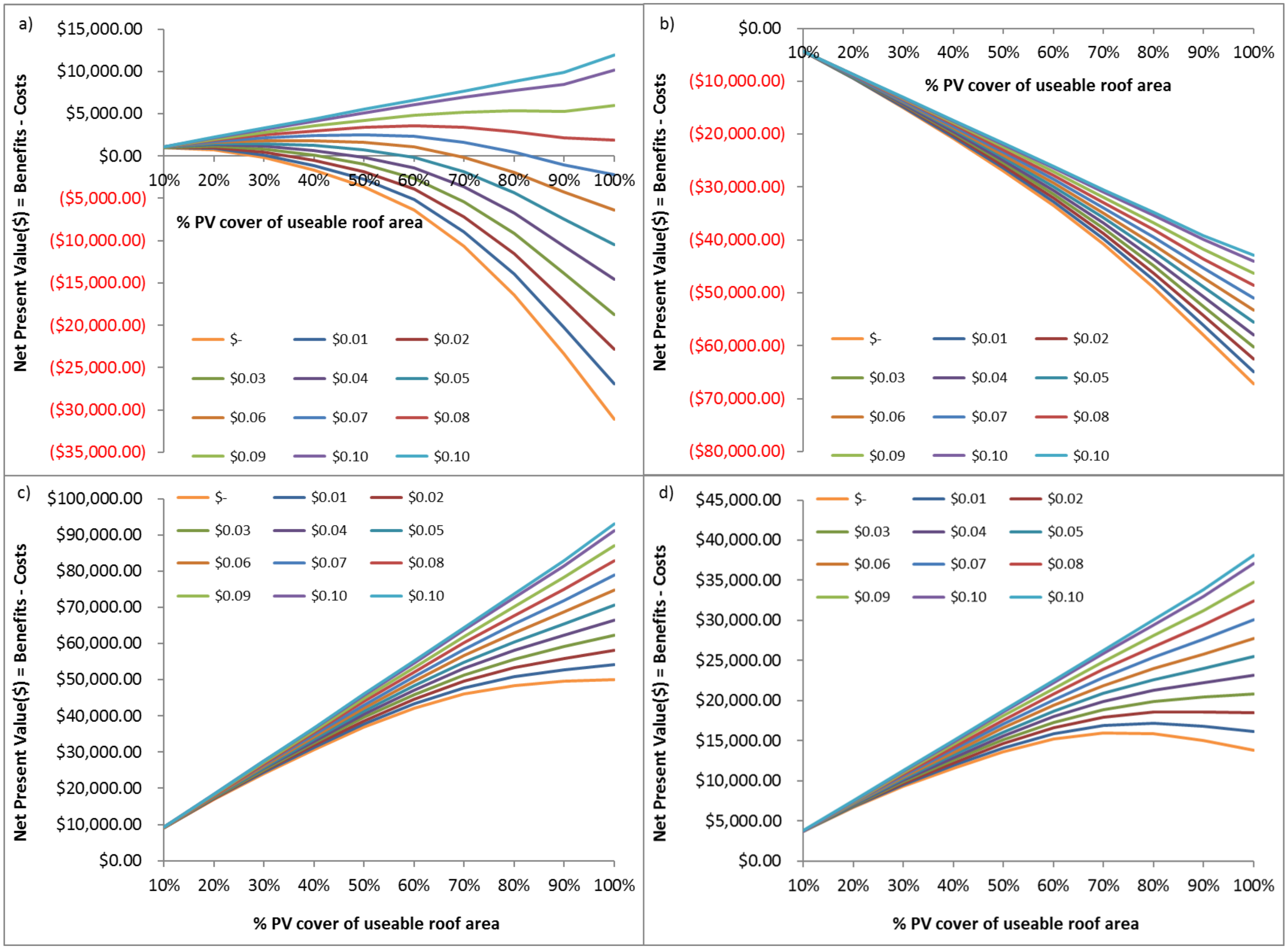


Figure 19: Net present value of implementing various sized PV systems for a small office building. a) NPV of implementing PV for a small office building assuming discount rate of 0% and cost of $3/W. b) NPV of implementing PV for a small office building assuming discount rate of 5% and cost of $2.95/W. c) NPV of implementing PV for a small office building assuming discount rate of 0% and cost of $1/W. d) NPV of implementing PV for a small office building assuming discount rate of 5% and cost of $1/W.

The net present value results were similar for the medium office, large office, multifamily residential and single-family residential buildings. In these cases an optimum PV size can be found when the discount rate is 0% and there is no solution with a 5% discount rate. When the future cost of PV is assumed there is no optimum PV size for all the buildings, except the single family residential, for the 0% and 5% discount rate. In the case of the single family residential with a 5% discount rate and $1/W cost of the PV system an optimum PV size can be determined for any F.I.T. less than or equal to 4 cents per kWh. In the case of the large office building with solar but no CCHP system, there is no variation in the benefits of implementing solar because almost all the energy generated from solar is used by the building. Therefore, all the benefits are in terms of avoided costs.

Similarly, for the medium office, large office, multifamily residential and single-family residential buildings at the current PV-system cost and discount rate of 5% it is never beneficial to implement a PV system for buildings in Atlanta (Appendix K). When the future cost of PV is assumed to be $1/w there is no optimum PV size for all the buildings, with the exception of the single family residential building. In the case of the single family residential with a 5% discount rate and $1/W cost of the PV system an optimum PV size can be determined for any F.I.T. less than or equal to 4 cents per kWh. Feed-in tariffs had no impact on the economic feasibility of large office building because most of the electricity generated by the PV system was used by the building (appendix K).

We further investigated at what PV system cost would the NPV would break even assuming a 5% discount rate over the 25-year PV lifespan. For the small office, building a PV system cost of $2.15/ watt would result in a positive NPV at the highest F.I.T. (Figure 20).Table 5 lists the maximum PV system cost that would result in a positive NPV. The department of energy estimated that by 2016 the cost of solar-PV would fall to $2.20/Watt[87]. Using this assumption along with a F.I.T. it would be economically beneficial to install rooftop PV on residential buildings. There is no difference in the breakeven cost of the large office building because the PV system produces very little energy that is not used by the building, no matter the size of the system. Similarly with the multifamily residential and medium office buildings, below a given PV coverage all the electricity generated by the PV system is used by the building so the F.I.T. has no impact on when the system has a positive NPV. With the multifamily residential building PV coverage of approximately 40% of the useable roof area or less means all the electricity generated is used by the building.. Therefore, no matter the F.I.T. reducing the cost of the system would result in a positive NPV for all F.I.T. curves when the PV area ranges from 0%-40% of the useable roof area. In the medium office, building this is 20% or less

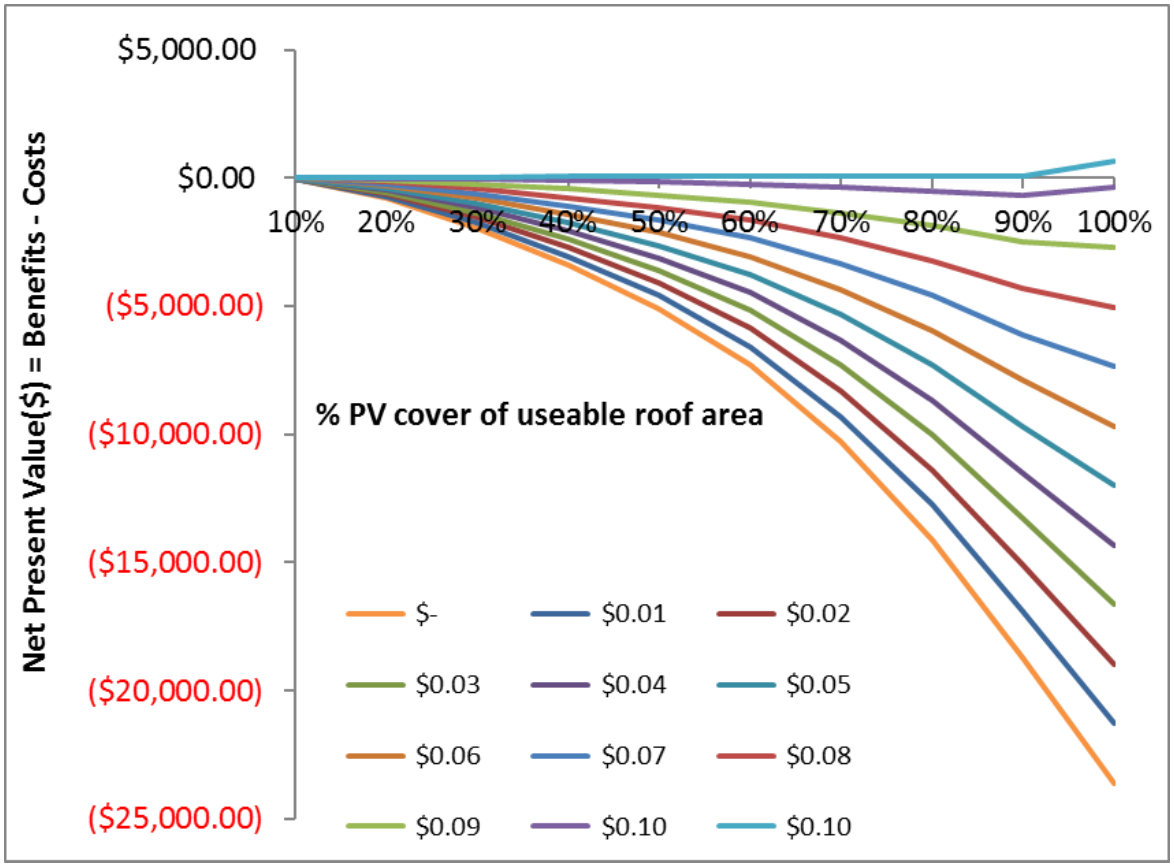


Figure 20: NPV of a PV installed on a small office building when a PV system cost of $2.15 per watt is assumed.

Table 5lists the maximum PV system cost that would result in a break even net present value. The department of energy has estimated that by 2016 the cost of solar-PV would fall to $2.20/Watt[87]. Using this assumption, along with the lowest and high feed-in tariff, it would be economically beneficial to install rooftop PV on residential buildings. There is no difference in the breakeven cost of the large office building because the PV system produces very little energy that is not used by the building, no matter the size of the system. Similarly with the multifamily residential and medium office buildings, below a given PV coverage all the electricity generated by the PV system is used by the building so the feed-in tariff has no impact on when the system has a positive NPV. With the multifamily residential building PV coverage of approximately

40% of the useable roof area or less means all the electricity generated is used by the building. Therefore, no matter the feed-in tariff reducing the cost of the system would result in a positive NPV for all feed-in tariff curves when the PV area ranges from 0%-40% of the useable roof area.

Table 5: Breakeven costs for a ll building types when a discount rate of 5% and time period of 25 years is assumed (the lowest feed-in tariff assumed for both residential and commercial building types was 0 ¢/kWh and the highest feed-in tariff for the residential and commercial buildings is assumed to be 12.55 ¢/kWh and 10.44 ¢/kWh respectively).

Building Type	**Breakeven Cost ($/Watt)**	
	Highest F.I.T.	Lowest F.I.T.
Small Office	2.15	2.10
Medium Office	2.14	2.14
Large Office	2.14	2.14
Multi-Family Residential	2.57	2.57
Single Family Residential	2.36	2.25

The benefits from the reduction in water consumption has significant implications depending on whether excess electricity produced by the PV system is sent to the grid. In addition, if the grid is assumed to be made up of combined cycle natural gas (CCNG) plants the benefits are minimal (Figure 21). When compared to the NPV values for various F.I.T. (Figure 19) the benefits from "water for energy" consumption are minimal. However, savings from a carbon tax will have a significant impact on the NPV of the system as the carbon tax savings with PV installed over the entire useable roof area is at least three times what is needed for the NPV to be positive (Figure 22) .

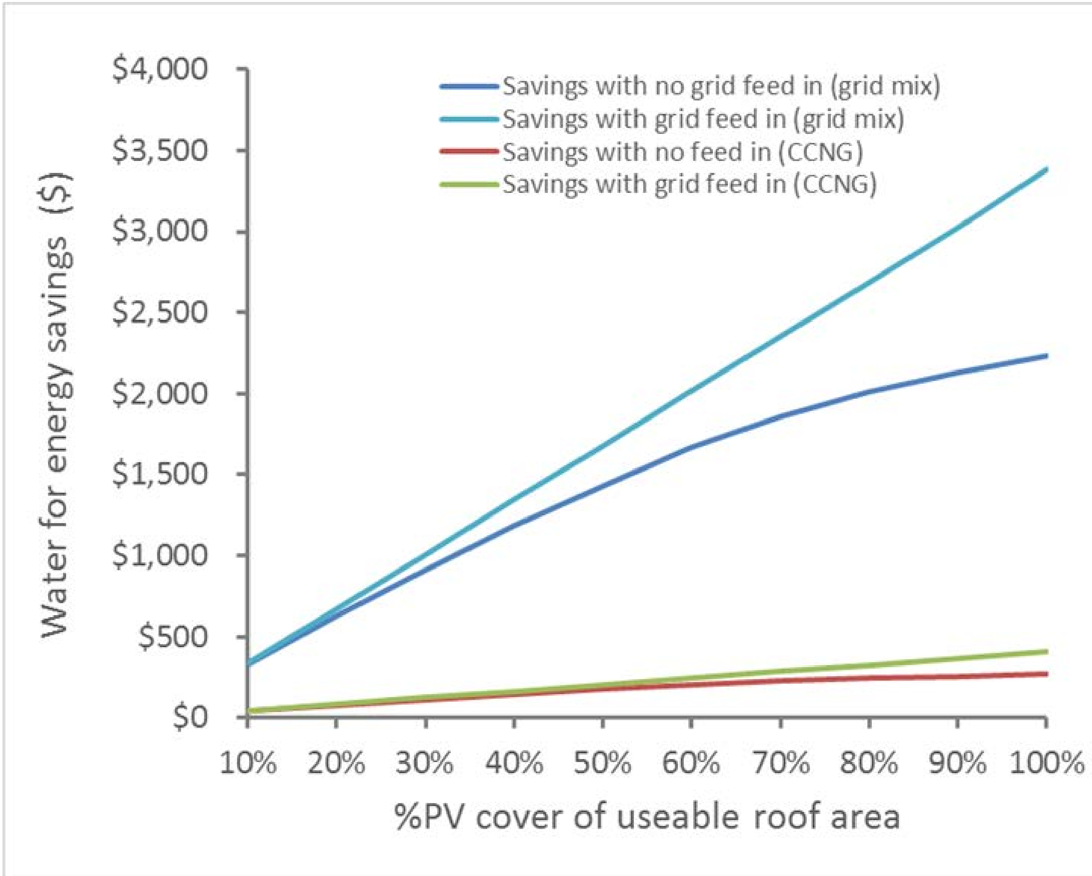


Figure 21: Water consumption for energy production savings for a small office building using a tax credit comparing the water saved from the grid mix of Georgia and a CCNG plant and assuming a water consumption credit of 0.6¢/gallon, 5% discount rate and 25 lifespan of the PV system.

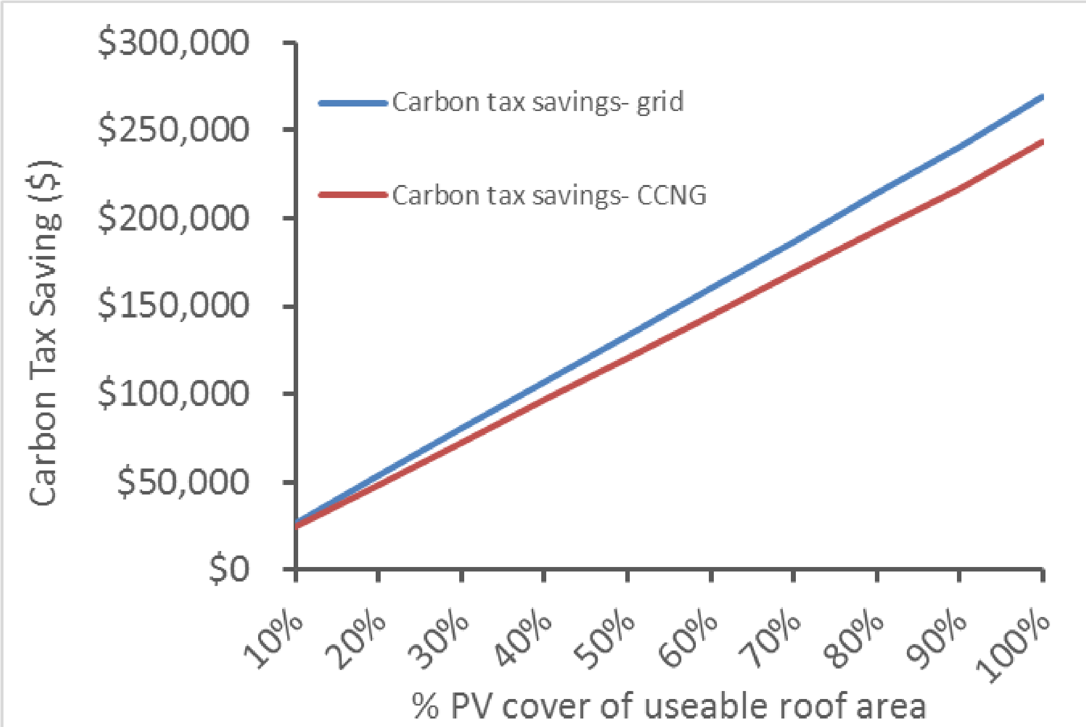


Figure 22: Annual carbon tax savings of a small office building using a PV system comparing the grid and CCNG assuminf a 5% discount rate, 25-year lifespan of the PV system, and default carbon pricing.

Accounting for a savings in the Carbon tax and implementing a water consumption credit results in a positive NPV for the small office building. There is no optimum PV size as there are increasing benefits the higher the percent PV installed (Figure 23). F.I.T's just provide a range in the value that can be realized. The only difference when accounting for different avoided costs increases the benefits by approximately 35% and 40% when assuming energy from the grid is based on the grid mix of Georgia or a CCNG plant respectively. There is a shift to use natural gas as a transition fuel in energy production but the analysis shows that there is not much savings in terms of CO_2 emissions. There is significant savings in water consumption and NO_x production.

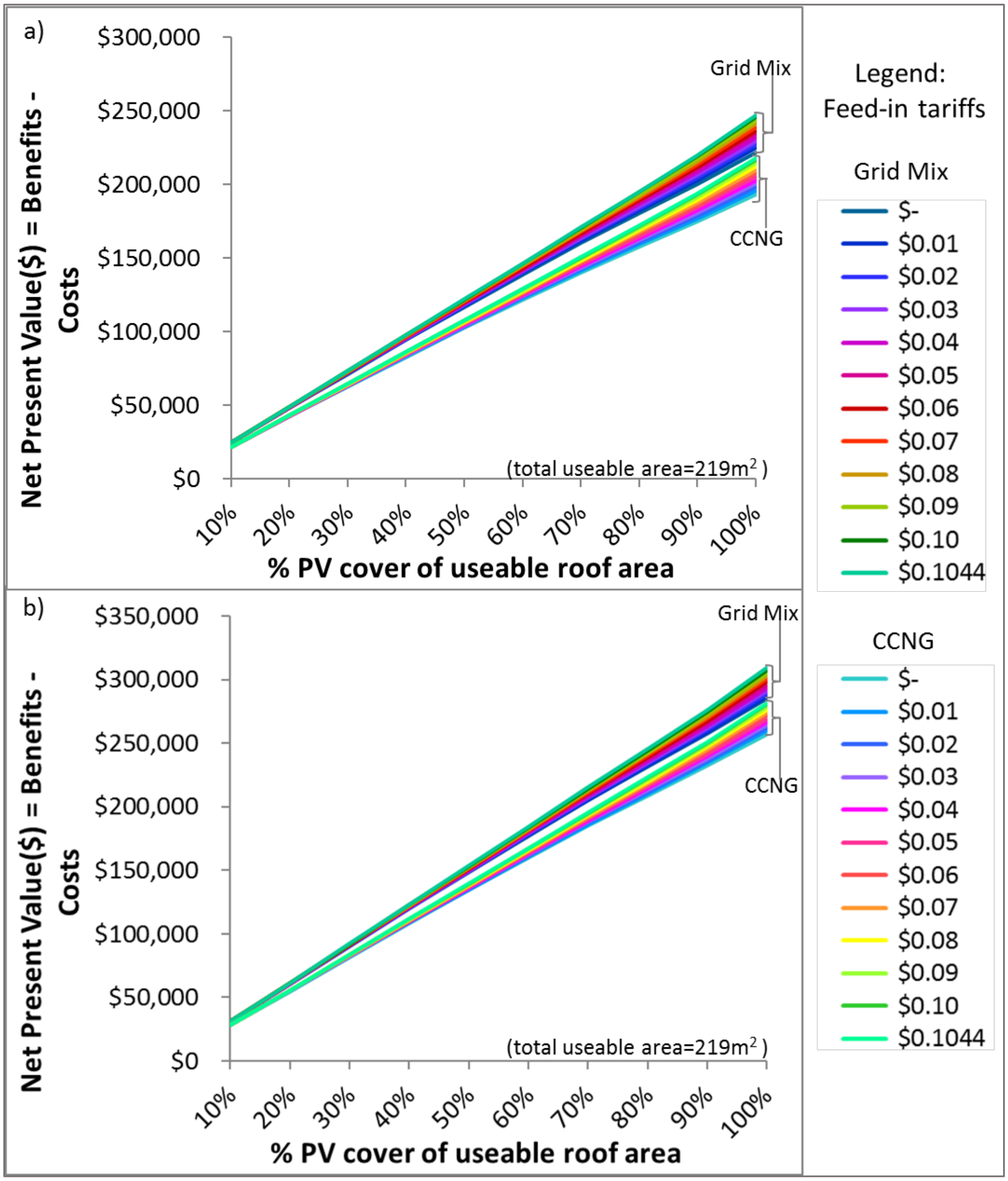


Figure 23: Net present accounting of carbon tax savings, and water consumption credit and the difference in the composition of grid technologies [grid mix or CCNG] for a range of feed-in tariffs. a) Net present value accounting for Carbon tax credit and water consumption credit assuming $2.95/W cost of system. b) Net present value accounting for Carbon tax credit and water consumption credit assuming $1/W cost of system.

PV-CCHP hybrid system

Adding PV panels to the current CCHP system actually reduces the efficacy of the PV panels. Because the CCHP system is able to meet more of the hourly demand, the energy generated by the PV that is actually used by the building is lower. Comparing Figure 24a and Figure 18a we see that the energy used per square meter of PV installed decreases for all building types. The nature of the change however, differs by building type. The electricity used, by a medium office building, from the PV system, when a CCHP system is used, is approximately the same as when there is only a PV system. The single family residential building has the greatest change between the two scenarios of PV only and CCHP+PV. In the case of the single family building, less energy is used by the building therefore more energy is available to be sold to the grid. Also compared with Figure 18a, only the large office building still uses a greater portion of the energy generated by the PV and CCHP systems, selling very little back to the grid.

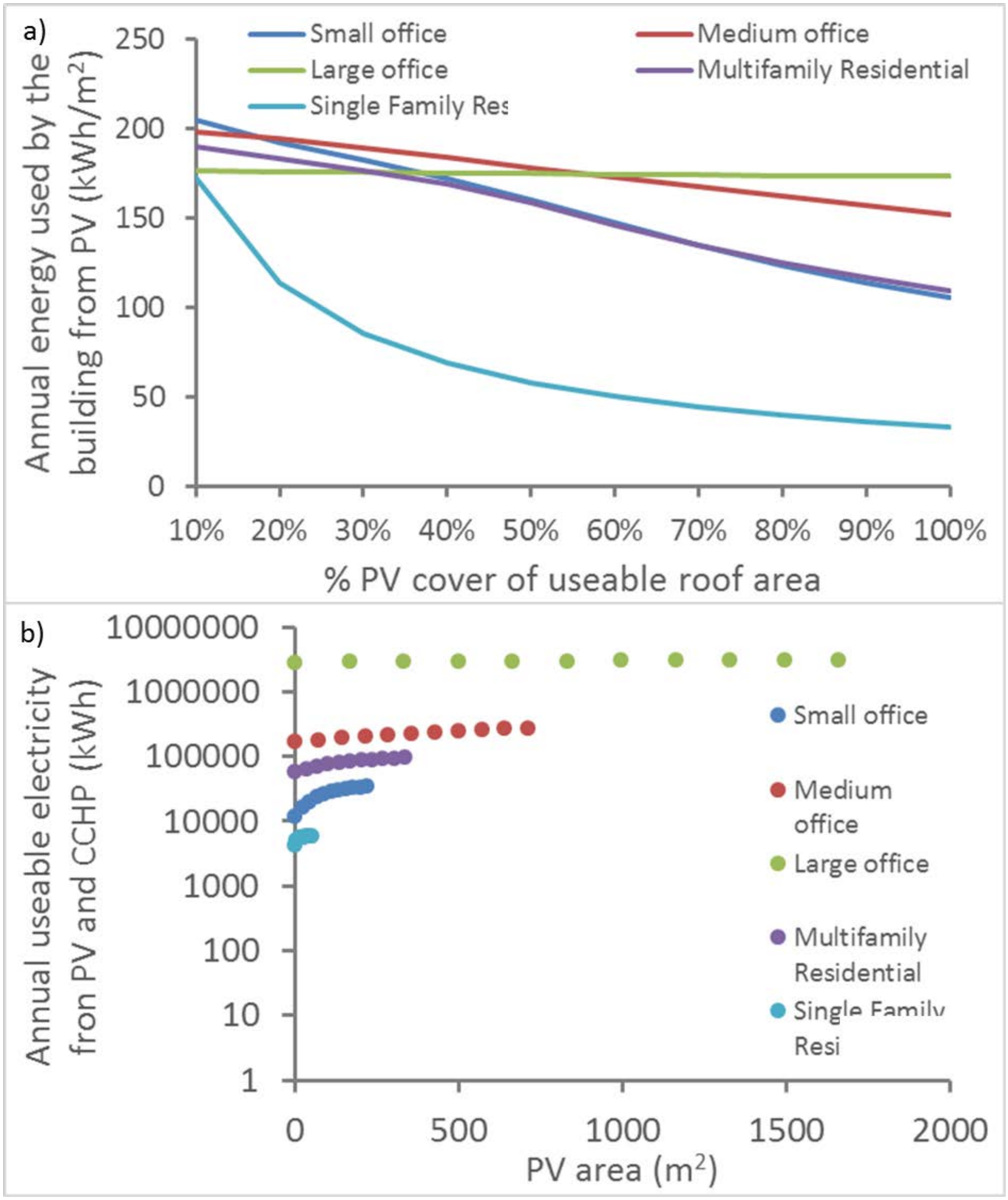


Figure 24: Annual electricity used from PV by each building type when a hybrid PV-CCHP system is used. a) Electricity used from PV by building per square meter of PV installed. b) Electricity used from the PV by 5 prototype buildings and the area of the PV system.

`The change in the annual savings from the avoided electricity diminishes when more PV is added to the rooftop of the small office, multifamily residential and single family residential buildings. The incremental benefits from adding more PV to the large and medium office buildings continue to increase. Combining the CCHP and PV system increases the "water for energy" savings and therefore the annual water consumption credits (Figure 26). Compared to the environmental impacts of conventional energy systems for a small office building the water consumption, CO_2 emissions and, NO_x emissions can be reduced by 84%, 79%, and 88% respectively, with a hybrid PV-CCHP system (Appendix O Table 14: Annual CO_2 emissions savings from a CCHP and hybrid CCHP-PV system for all building prototypes). Reductions in emissions and water consumption are highest for the small office and single family residential buildings because these buildings produce the most excess electricity (Appendix O Table 14: Annual CO_2 emissions savings from a CCHP and hybrid CCHP-PV system for all building prototypes). As with the PV-only scenarios adding a carbon tax savings, NO_z damage cost savings and water consumption credit resulted in a positive NPV for the small office building at a PV system cost of $2.95/Watt. Scenarios with these savings and credit had no optimum PV system size as the incremental benefits outweigh the incremental costs of adding more PV to the system (Figure 31).

The water consumption credit and avoided damage cost policies are not as significant as the carbon tax savings and the avoided electricity savings (Figure 30). The water consumption credit assumed, 0.6¢/gallon, is less than 6% of the price of electricity. Therefore, the impact of the water credit compared to that of the Carbon tax or feed-in tariff is minimal. Therefore, the estimated savings per kWh. The estimates for the NO_X damage cost savings are low because the total reduced NO_X emissions are low and the median damage cost assumed (Appendix H), this meant the avoided damage costs had very little impact on the total benefits, especially when compared to the carbon savings

(Figure 30) (Appendix N). A feed in tariff and carbon tax policy can have more of an impact on the economic feasibility of the system than a water consumption policy. The feed in tariffs are dependent on the electricity over produced by the PV-CCHP system therefore, the annual feed-in tariff benefit will vary depending on the amount of energy over produced by the system. For example, the small office building PV-CCHP system produces 70% more electricity than is used by the building from the system- assuming PV covers 100% of the useable roof area. The excess electricity is produced because of the difference in the hourly electrical demand of the building and the hourly electrical output of the PV-CCHP system. Therefore, the higher the FIT the more economic this system will be as the benefit from the overproduced electricity is closer to the benefit from an avoided electricity cost. The large office building on the other hand only produces ~12% more energy that the building uses which means that the majority of the benefit is from an avoided electricity cost.

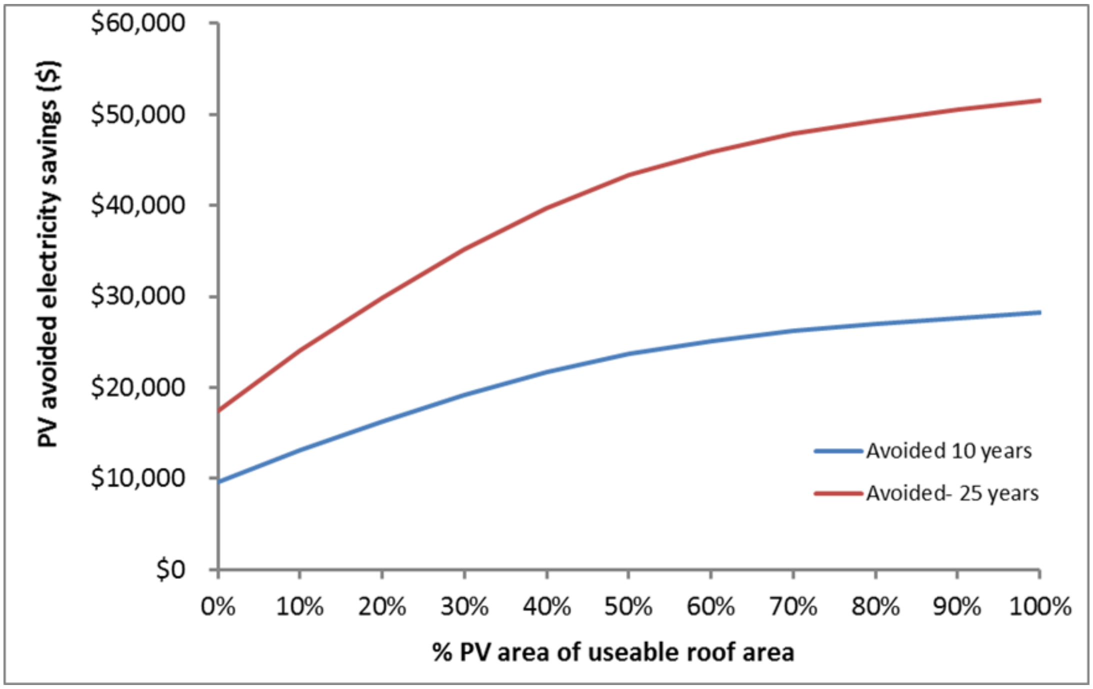


Figure 25: Present value of savings due to the electricity no longer being purchased from the grid over two periods, 10 and 25 years and for a 5% discount rate.

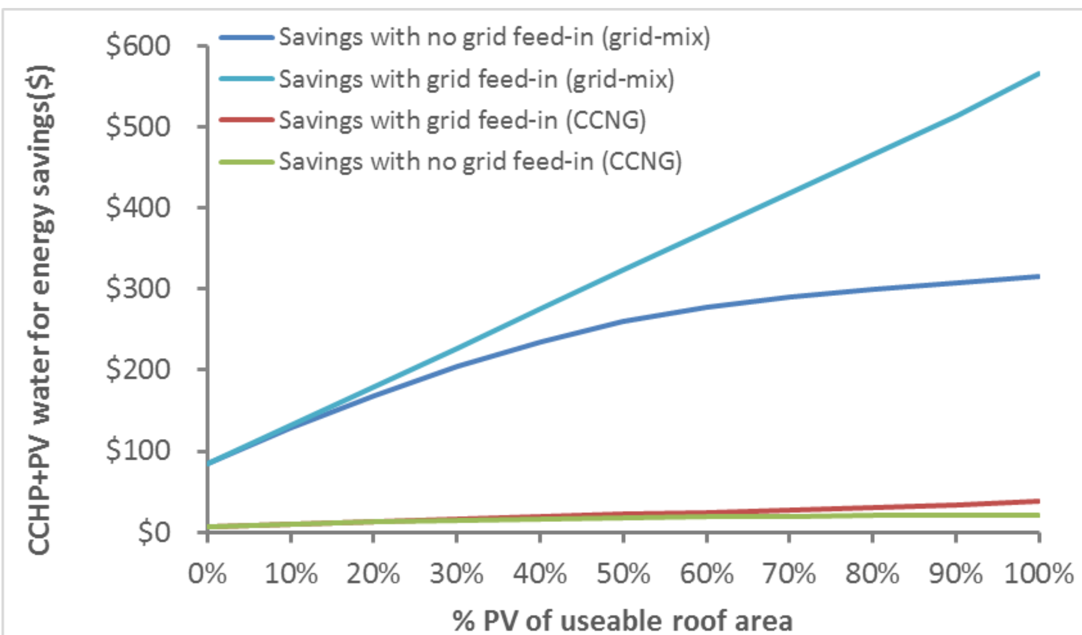


Figure 26: Present value of water consumption savings for the Atlanta grid mix and combined cycle natural gas (CCNG) plant with and without grid feed-in.

A feed in tariff and carbon tax policy can have more of an impact on the economic feasibility of the system than a water consumption policy (Figure 27, Figure

28). The feed in tariffs are dependent on the electricity over produced by the PV-CCHP system therefore, the value of F.I.T's will vary depending on the amount of energy over produced by the system. The impact of a feed in tariff on the system will also depend on the amount of energy generated by the system and what fraction of the energy generated is used by the building. For example, the small office building PV-CCHP system produces 70% more electricity than is used by the building from the system- assuming PV covers 100% of the useable roof area (Table 6). Therefore, the higher the FIT the better off this system will be economically. The large office building on the other hand only produces ~12% more energy that the building uses.

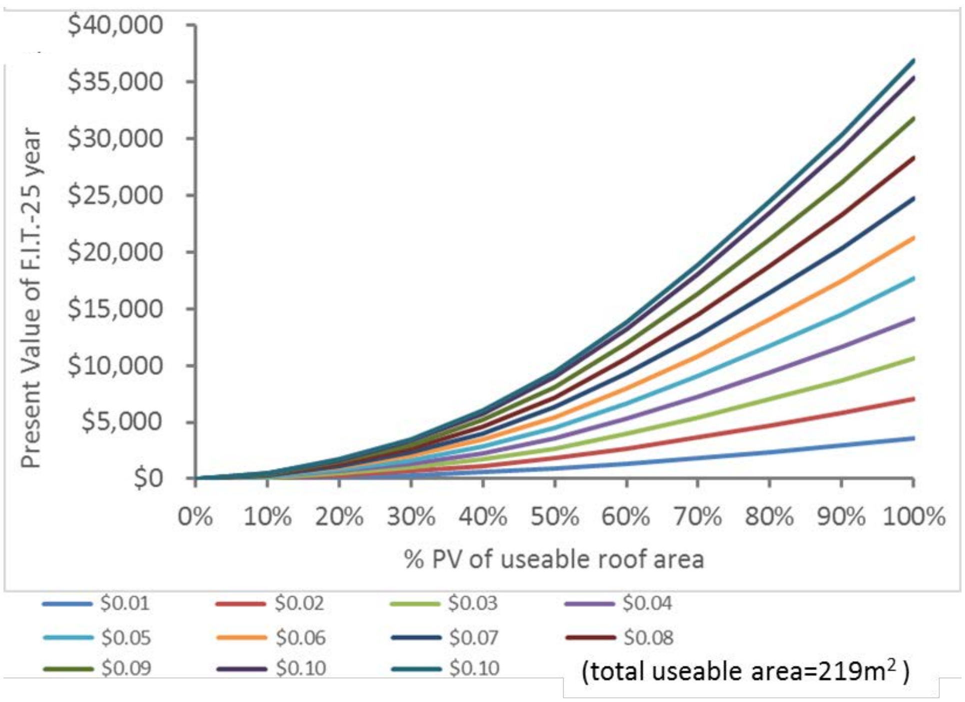


Figure 27: Present value of the benefits of feed-in-tariffs (F.I.T.) for a small office building assuming 25 years.

Table 6: Percent of electricity overproduced compared to the generated electricity used by the building

Building Type	*Small Office*	*Medium Office*	*Large Office*	*Multifamily Residential*	*Single Family Residential*
Overproduction(100% PV area)/ Avoided electricity	71%	20%	12%	40%	130%

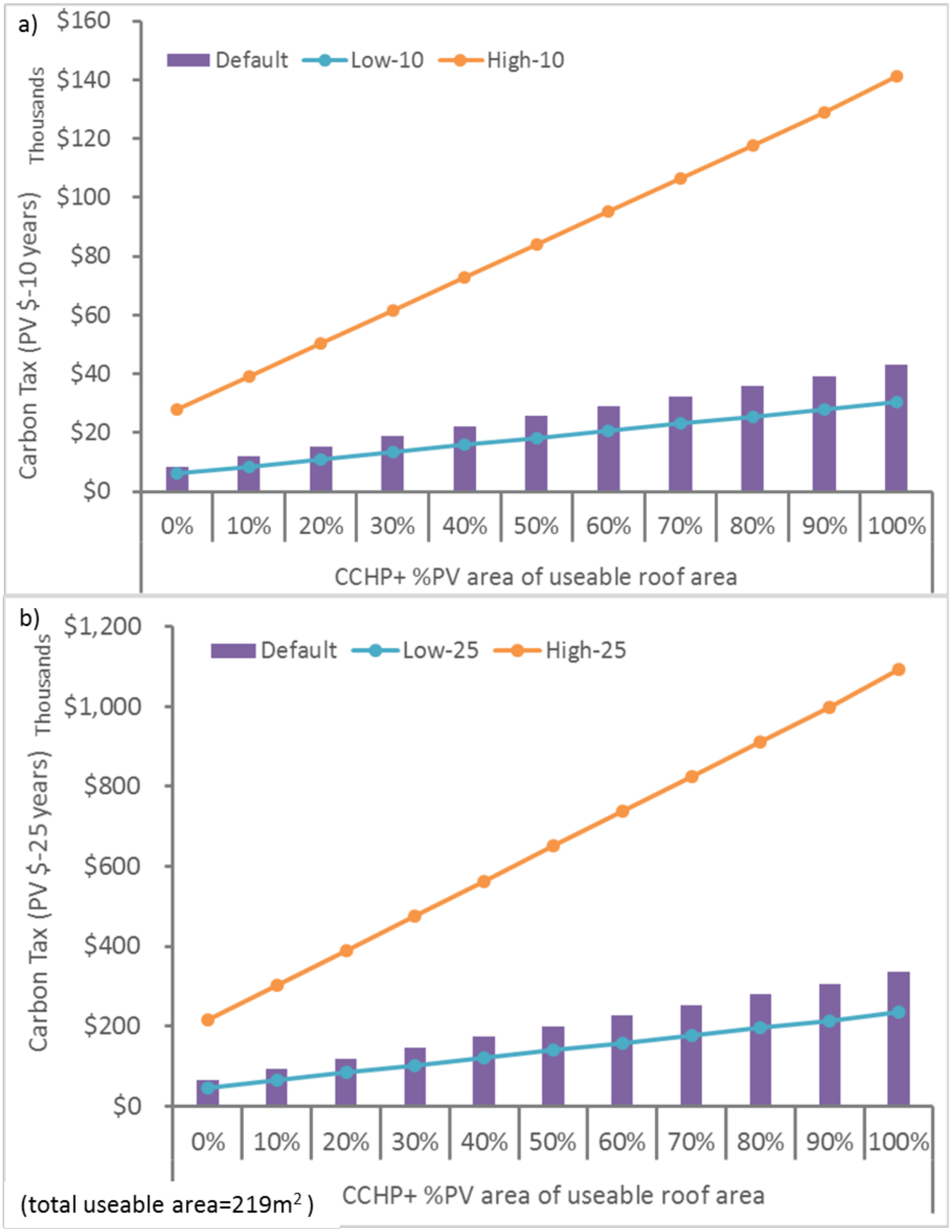


Figure 28: Present Value cost of carbon tax for varying PV sizes with CCHP showing high and low estimates. a) PV carbon cost over a 10 year period. b) PV cost of carbon over a 25 year period.

Similar to the water for energy credit, the benefits to accounting for the damage costs of NO_x are minimal when compared to the other monetized benefits (Figure 29). The reason for this is that the NO_x emissions are significantly lower by mass than CO_2 emissions. The damage costs are also lower than the carbon tax.

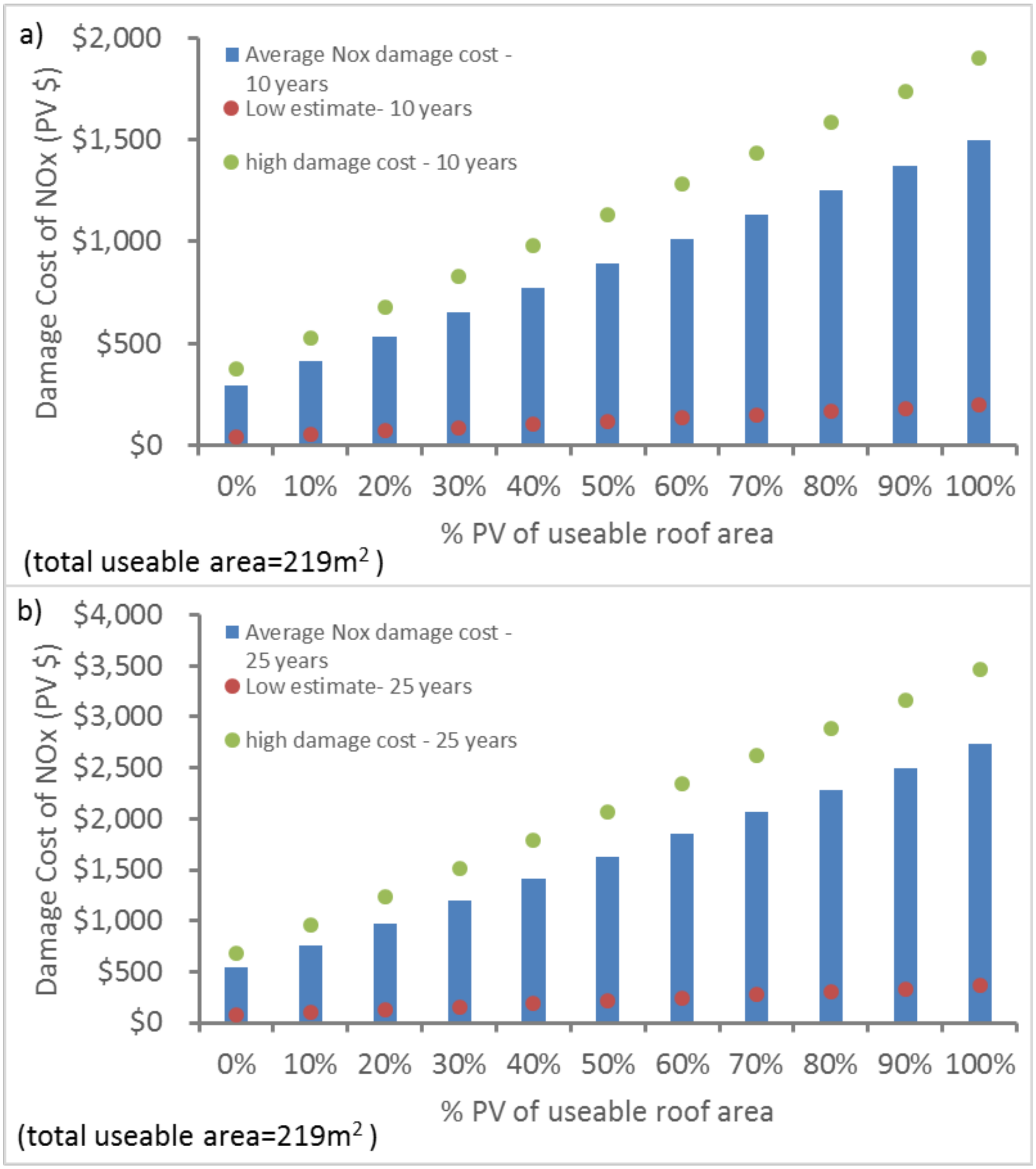


Figure 29: Damage cost saved from NOx emissions for a small office building.

No optimum PV area can be found for use in a hybrid PV-CCHP system for a small office building when all the annual net benefits and costs are considered as it is most economically beneficial to implement 100% of the total useable rooftop area.

However, we can determine the minimum PV size that should be for the system to be economically feasible. When we accounted for all policy scenarios and a PV system cost of $2.85 per watt the hybrid system would not be economically viable, for a small office building, if less than approximately 45%-50% of the useable roof area is covered with PV (Figure 31). Comparably the system would not be economically viable at the $1 per watt cost if the PV coverage of the useable roof area were less than ~35%. (Figure 31). For all other buildings, hybrid PV-CCHP systems would be economically feasible no matter how much of the rooftop is covered by PV. However, the maximum net value would be gained by maximizing the amount of PV placed on the building's rooftop.

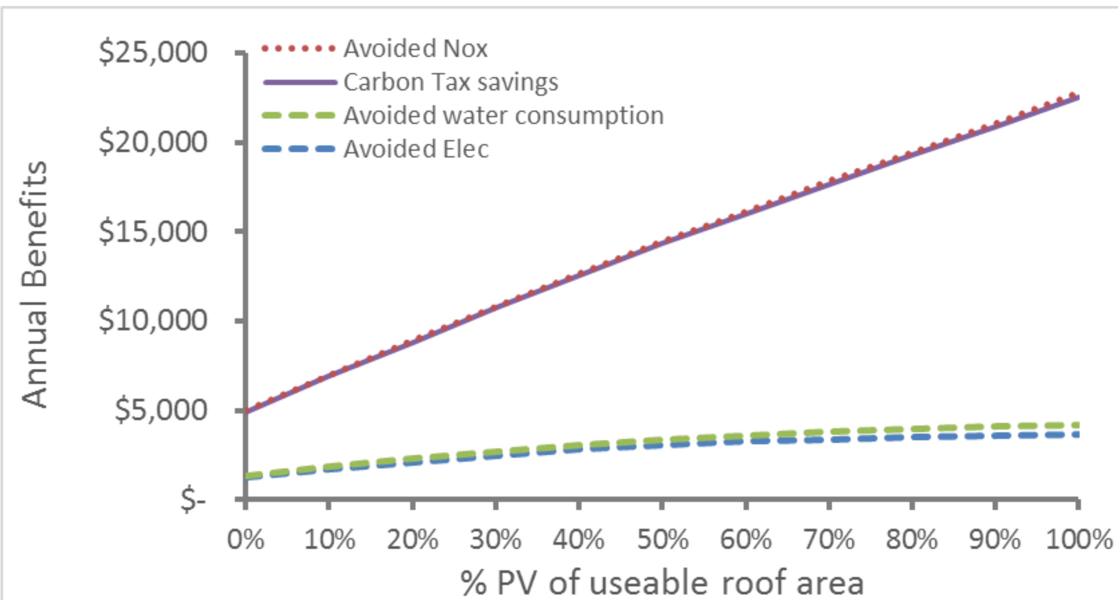


Figure 30: Cumulative avoided electricity generation, water consumption credit, avoided NOx damage costs, and carbon tax savings for a small office building.

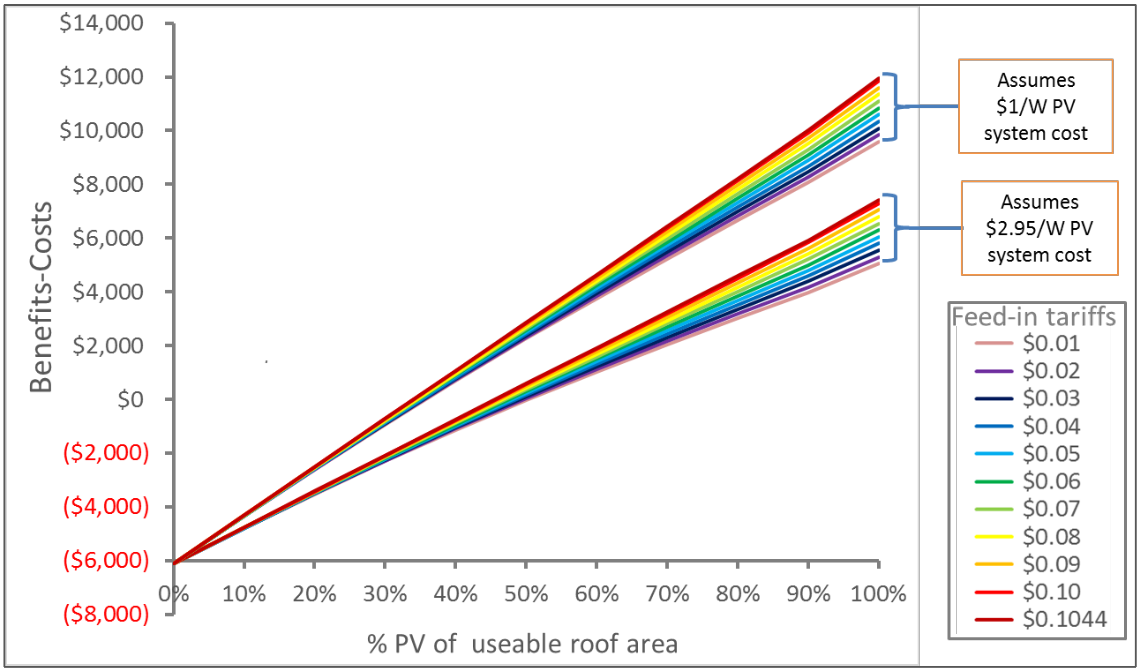


Figure 31: Annual net value of a hybrid PV-CCHP system for a small office building assuming savings from carbon tax, damage costs, water consumption credit, and avoided HVAC costs assuming the two PV system costs.

CHAPTER 5

MAJOR CONCLUSIONS AND FUTURE WORK

Major Conclusions

- CCHP systems can significantly reduce the CO_2 emissions, NO_x emissions, and water consumption for energy production of the 5 building prototypes.
- When there is no net metering policy following the thermal load (FTL) operation strategy results in the greatest CO_2 and cost savings, but running the system to constantly meet the maximum annual thermal demand results in the greatest NO_x and “water for energy” reductions.
- A net metering policy can significantly influence the emissions reduction potential, water for energy savings, cost, and optimum operation strategy of CCHP systems.
- Wide-scale implementation of CCHP systems would reduce regional CO_2 emissions, NO_X emissions, and “water for energy” consumption.
- Solely switching to more compact growth scenario, in which a greater portion of the population lives in multifamily units will not decrease the energy consumption when compared to the business as usual scenario for the 13-county Atlanta metropolitan region. The energy consumption will decrease if there is an increase in the number of people per housing unit.
- At current system costs, PV systems are currently not economically viable and an optimum PV size cannot be determined. However, a decrease in these costs over the next few years will improve the economic viability of the system. This cost will vary depending on the building type.

- Policies such as feed-in tariffs and carbon taxes will improve the economic viability of a PV-CCHP hybrid system. Current estimates of NO_x damage costs and "water for energy" pricing would not significantly impact the economic feasibility of the system.

Future Work

Expanding the study to various geographic regions

Implementing CCHP or hybrid PV-CCHP systems in other geographic regions could result in greater emissions and water for energy reductions. The policies in different areas can have a significant impact on the economic feasibility of implementing CCHP systems within a given region. Analyzing the impact regional policies can have as well as potential policies that will make the system seem more economical feasible will influence the adoption of CCHP systems.

Expanding the CCHP system to include thermal storage, renewables and electric vehicles

Currently, work is being done to analyze the impact of various thermal storage technologies on the effectiveness of CCHP systems. The system can be further expanded to include electrical storage either in the form of a batter or electric vehicle (Figure 32). With CCHP systems optimizing the amount of thermal energy stored daily or seasonally could affect the overall emissions produced by the system compared to the conventional grid. Thermal storage systems along with electric storage such as electric vehicles may also minimize the costs and make the hybrid system more economically viable. The economic benefits will be greater because typically feed in tariffs are lower than grid prices.

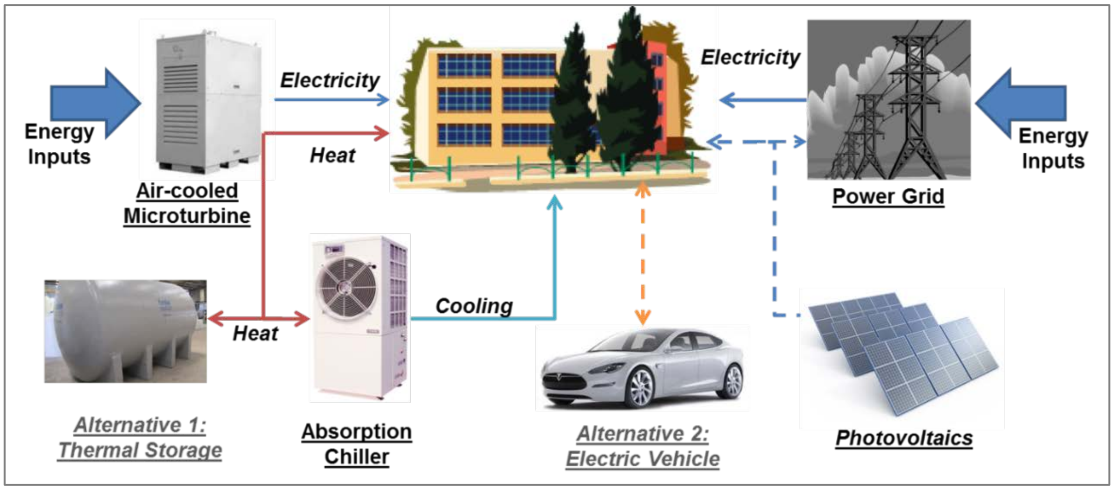


Figure 32: Expanded CCHP system

Understanding the resiliency of urban energy systems with a partially decentralized energy system using ecological network analysis (ENA)

Using ecological network analysis the metabolism of the business as usual scenario for the Atlanta metropolitan region can be modeled. The impacts of implementing CCHP systems, and various policies related to CCHP, can be studied by extending the regional input output tables similar to Leigh et al[88].

Additional tri-generation technologies

Other system configurations could be used to produce heat and electrical energy. For example, PV thermal hybrid systems have been studied for small scale systems. Investigating the feasibility of this technology on a broader scale could mean further reductions in emissions and water consumption for energy production [44]. Using solid oxide fuel cells (SOFC) as the primary generating unit in a CCHP system can also result in improved efficiency and reduced emissions [89].

Resiliency of energy grid with CCHP

CCHP systems are more resilient than conventional energy systems because of their decentralized nature. We can model the resiliency of an electric grid system when CCHP systems are introduced at various scales in the system. This can be done using a hypothetical network such as the IEEE123-bus test feeder to represent an urban distribution network and running an analysis on the location of the CCHP systems as well as the potential failure of one or more nodes or links in the system. Depending on the hazard that would be associated with a failure the system may also need to concurrently model the gas distribution network.

APPENDIX A: BUILDING ENERGY DEMAND AND CCHP OPERATION STRATEGIES

Appendix A Figure 33 shows the modified hourly thermal demand of a medium office building. This hourly thermal demand was used for the hourly thermal demand operating scenario (Figure 34). Figure 34 shows the CCHP system thermal output to match the hourly demand for a medium office building. Figure 34a illustrates the hourly demand profile (pink) and the thermal output of the CCHP system (purple) for the month of June. Figure 34b is a snapshot of how the CCHP system operates to meet the hourly demand for one day in the month of June. In all the figures the pink represents the hourly thermal demand. The green is the thermal demand of the specified operating scenario and the purple is the turbine output to meet the demand of the given operating scenario. The turbines have a minimum capacity at which they can be operated before they switch off. This is the lowest operating mode of the turbines and can be seen in Figure 33. Since the turbines cannot be turned on and instantaneously meet a thermal demand they assumed their output never falls below the minimum operating capacity. Figure 34 represents the maximum daily demand operating scenario for the month of June. The green line represents the maximum daily demand of the building and the purple is the turbine output for the operating scenario. Similarly Figure 36a and b represent the maximum monthly and maximum annual thermal demand, respectively.

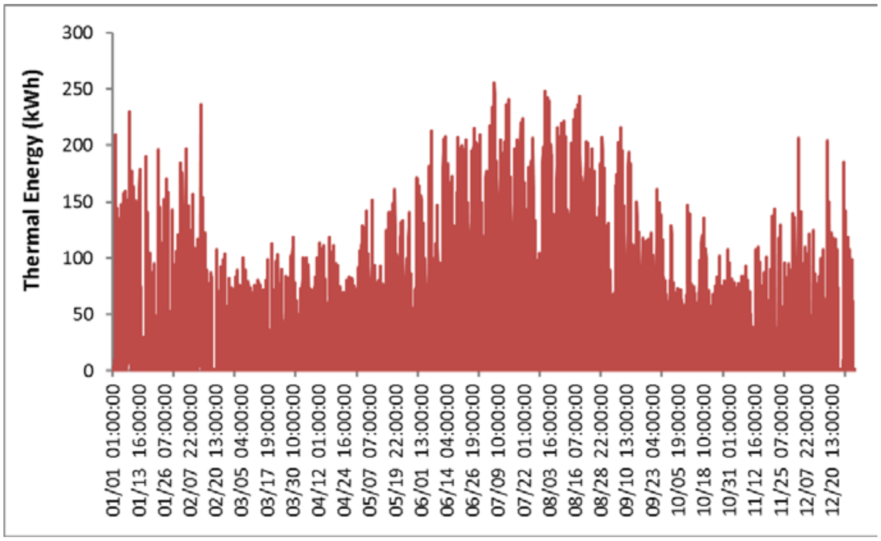


Figure 33: Thermal (heating and cooling) demand of a medium office building when using a CCHP system

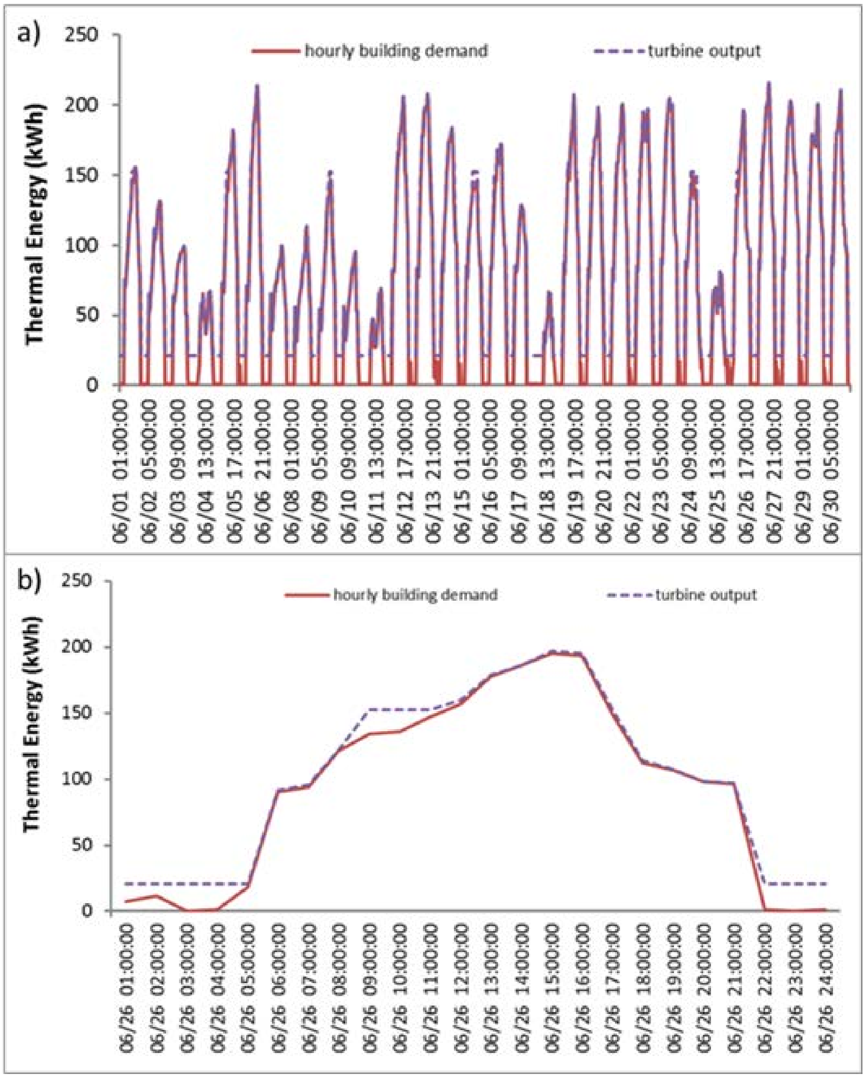


Figure 34: Thermal energy output of the CCHP system operated to meet the hourly thermal load of a medium office building. a) compares the thermal demand of the building and thermal output of the building over the month of June. b) compares the thermal demand of the building and thermal output of the building over a day in June

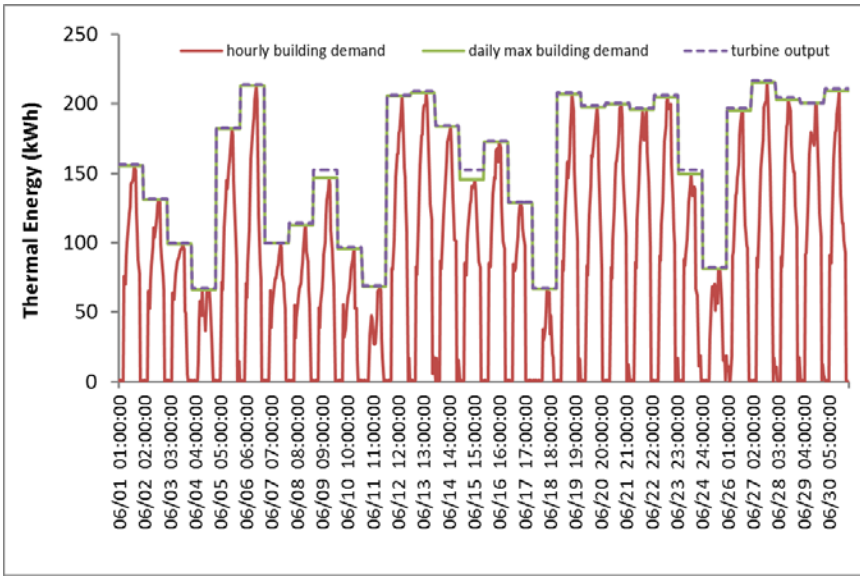


Figure 35: Thermal energy output of the CCHP system operated to meet the daily thermal load of a medium office building in the month of June.

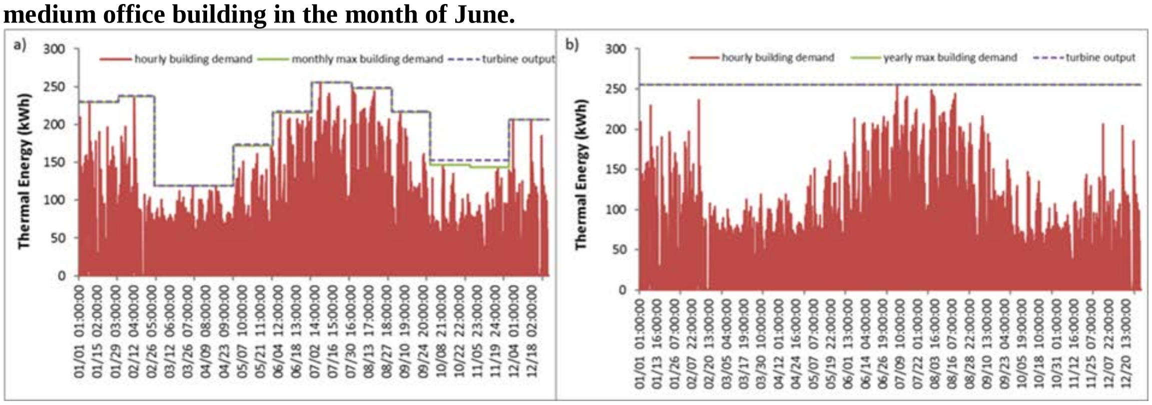


Figure 36: Operational scenarios of CCHP system against the thermal demand when a CCHP system is used. a) CCHP system is operated to meet the hourly load of a medium office building. a) CCHP system is operated to meet the maximum monthly thermal demand of a medium office building. b) CCHP system operated to meet the maximum annual demand of a medium office building

APPENDIX B: EQUATIONS USED TO CALCULATE THE ANNUAL COST OF HEATING AND COOLING TECHNOLOGIES

$$P_{furnace\ annual} = \frac{P_{furnace} * i}{1 - (1 + i)^{-n}}$$

$$P_{AC\ annual} = \frac{P_{AC} * i}{1 - (1 + i)^{-n}}$$

$$P_{Turbine\ Annual} = \frac{P_{turbine} * i}{1 - (1 + i)^{-n}} + Cost_{O\&M}$$

$$P_{Chiller\ Annual} = \frac{P_{Chiller} * i}{1 - (1 + i)^{-n}} + Cost_{O\&M}$$

APPENDIX C: PER SQUARE FOOT "WATER FOR ENERGY" CONSUMPTION

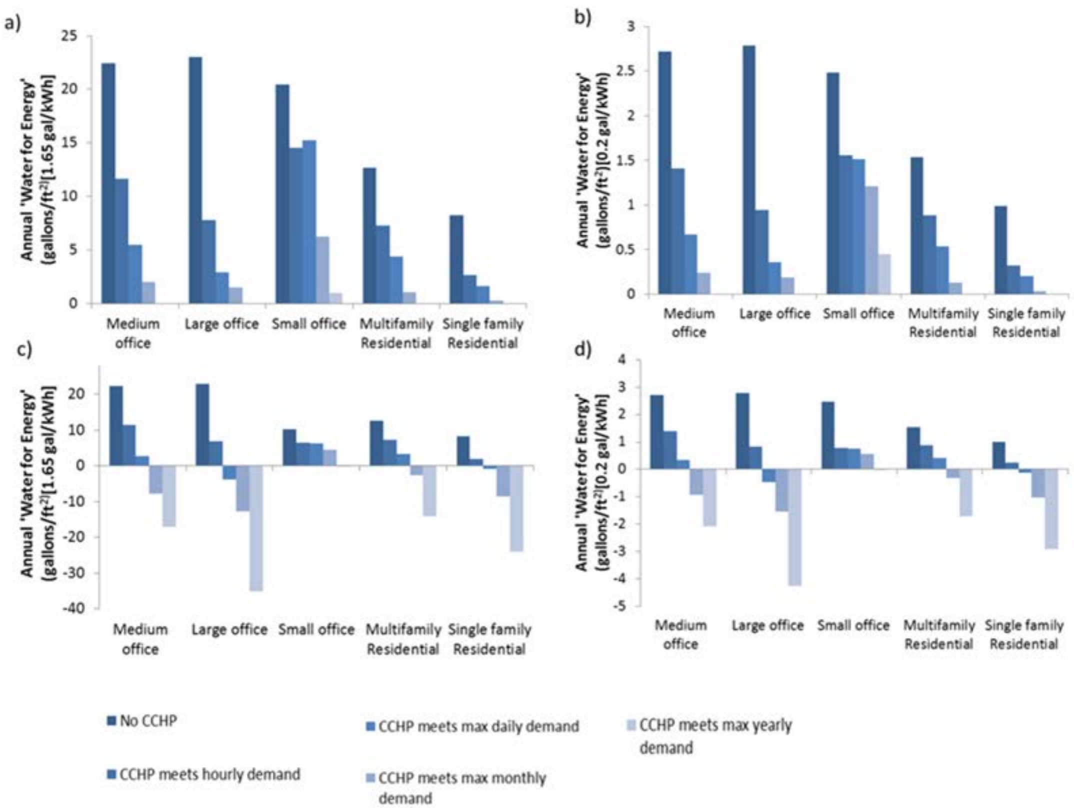


Figure 37: Water for energy consumption for 5 building types operating under five CCHP scenarios. a) Water for energy consumption using a consumption factor of 1.65 gallons per kWh and no net metering. b) Water for energy consumption using a consumption factor of 0.2 gallons per kWh and no net metering. c) Water for energy consumption using a consumption factor of 1.65 gallons per kWh and net metering. d) Water for energy consumption using a consumption factor of 0.2 gallons per kWh and net metering. Water for energy consumption is negative in the net metering scenarios because this is the water consumption mitigated by the grid producing less electricity.

APPENDIX D: PER SQUARE FOOT CO_2 EMISSIONS

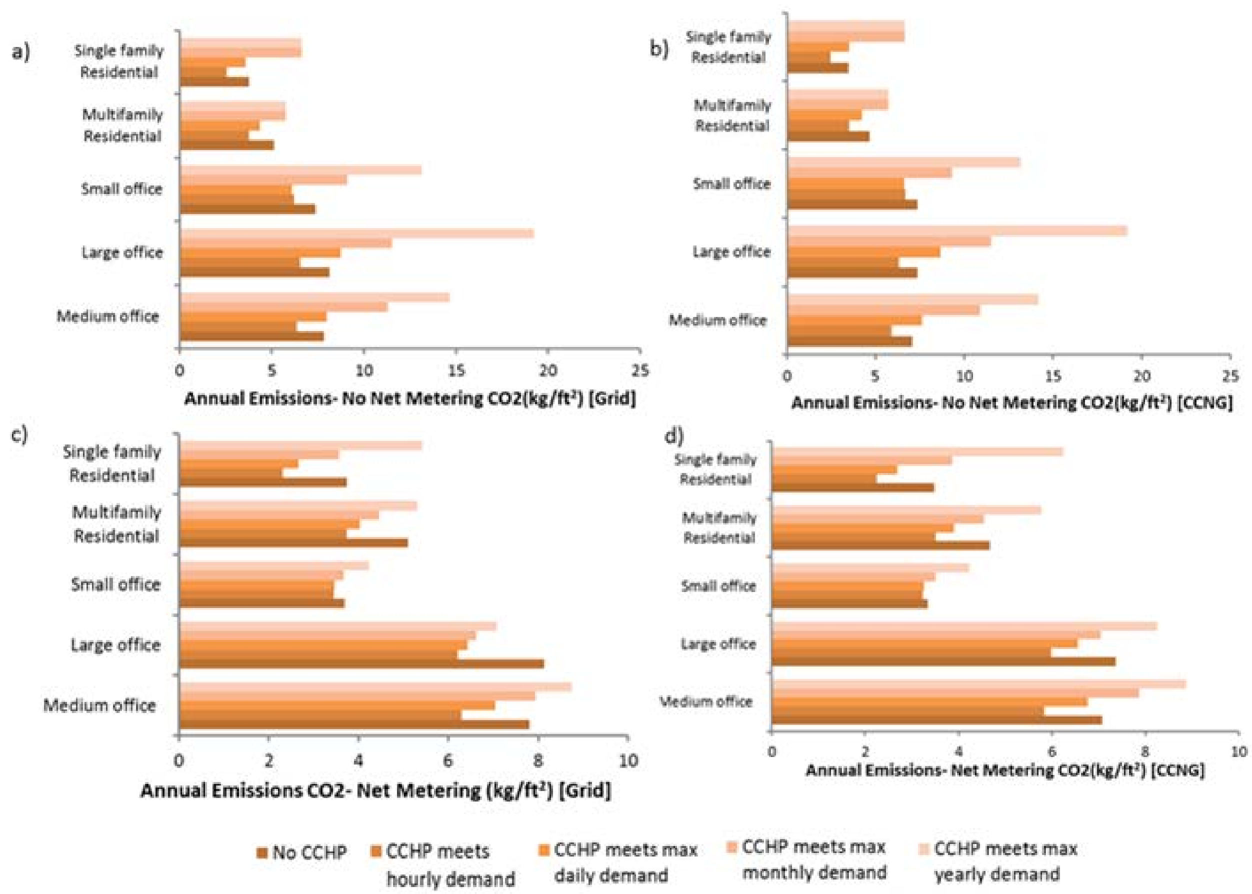


Figure 38: Per square foot carbon dioxide emissions of all building types under all operation scenarios. a) Carbon dioxide emissions with a CCHP system and no net metering assuming emissions from CCHP system and Grid Mix. b) Carbon dioxide emissions with a CCHP system and no net metering assuming emissions from grid is that of a combined cycle natural gas plant. c) Carbon dioxide emissions with a CCHP system with net metering assuming emissions from CCHP system and grid mix. d) Carbon dioxide emissions with a CCHP system with net metering assuming emissions from grid is that of a combined cycle natural gas plant.

APPENDIX E: PER SQUARE FOOT NO_X EMISSIONS

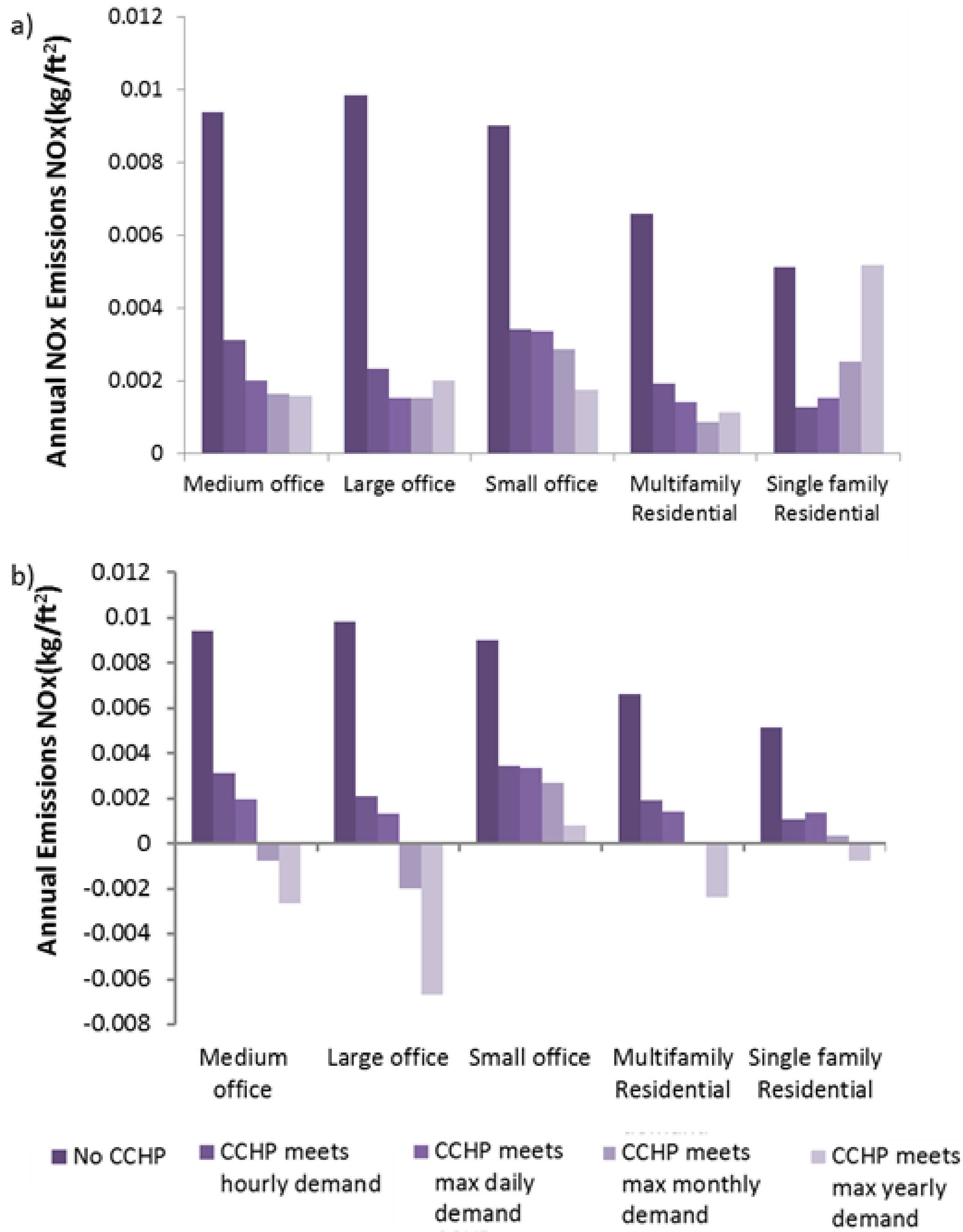


Figure 39: Per square foot NOx emissions of all building types under all operation scenarios assuming grid emissions are based on the grid mix. a) NOx emissions without net metering. b) NOx emissions with net metering.

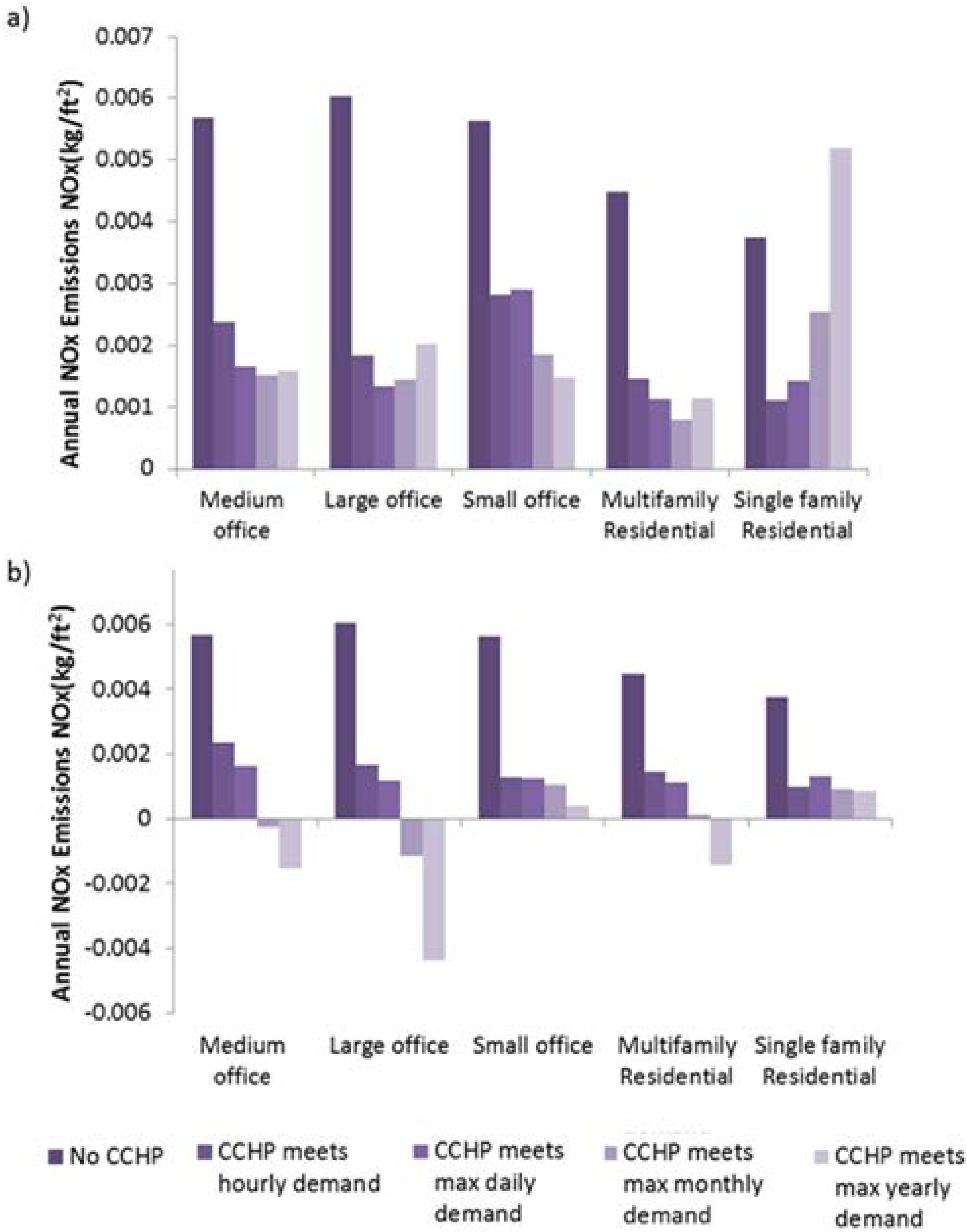


Figure 40: Per square foot NOx emissions of all building types under all operation scenarios assuming grid emissions are from a CCNG. a) NOx emissions without net metering. b) NOx emissions with net metering.

APPENDIX F: PER SQUARE FOOT COST ESTIMATES OF CCHP SYSTEMS COMPARED TO CONVENTIONAL ENERGY SYSTEMS

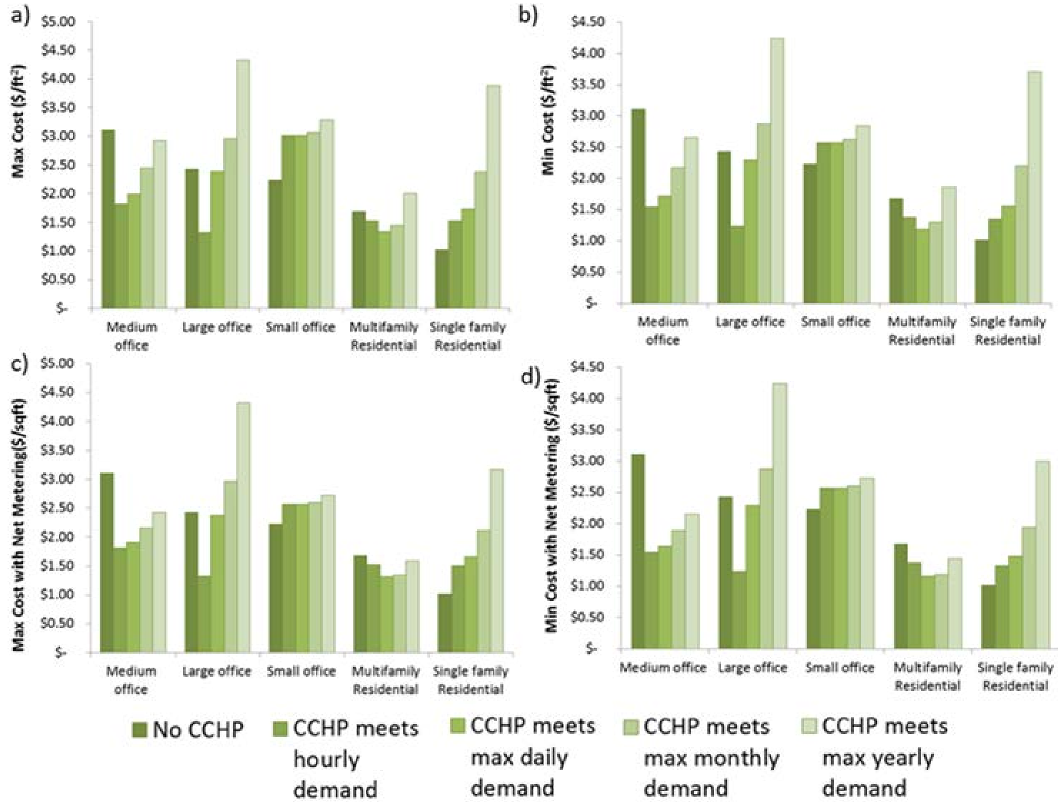


Figure 41: Per square foot cost estimates of CCHP systems compared to the cost of energy in the no CCHP scenario for all 5 building types. a) Maximum CCHP system cost estimates with no net metering. b) Minimum CCHP system cost estimates with no net metering. c) Maximum CCHP system cost estimates with net metering. d) Minimum CCHP system cost estimates with net metering.

APPENDIX G: CHANGE IN THE SQUARE FOOTAGE OF OFFICE SPACE, BETWEEN 2005 AND 2030, FOR ALL BUILDING TYPES

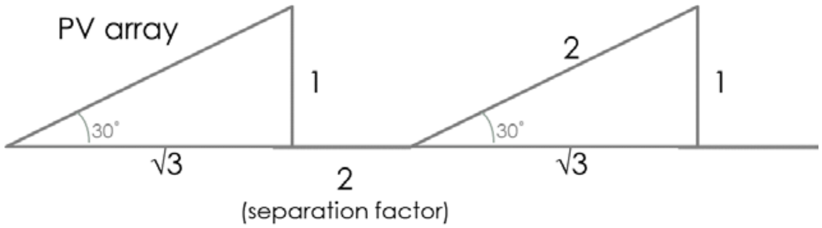
Table 7: Total projected square footage for each office type between 2005 and 2030.

COUNTY	Small office	Medium office	Large office
CHEROKEE	9704950.954	13489272	4353564.457
CLAYTON	3999791.99	6752411	2354838.252
COBB	61482411.62	29074521	66599403.06
COWETA	6093750.926	5949995	8614764.929
DEKLAB	42260747.91	30172276	60733001.16
DOUGLAS	6239992.557	5158921	8951649.051
FAYETTE	8445942.072	8372056	11964182.36
FORSYTH	12287396.13	12883463	18113798.82
FULTON	114052058.9	92921726	153227347.3
GWINNET	52693475.66	45596700	73347017.79
HENRY	13141245.17	15133336	19389756.44
PAULDING	5843888.915	7681952	9325942.783
ROCKDALE	6190499.561	5799013	8915177.228
TOTAL	342436152.4	2.79E+08	445890443.7

APPENDIX H: CHANGE IN SINGLE-FAMILY AND MULTIFAMILY HOUSING UNITS BETWEEN 2005 AND 2030 FOR THE BAU AND MCG SCENARIOS

	BAU			MCG		
	SINGLE FAMILY	MULTI FAMILY	TOTAL	SINGLE FAMILY	MULTI FAMILY	TOTAL
CHEROKEE	67887.86	7543.095	75430.95	52823.7	22638.73	75462.43
CLAYTON	13678.46	5862.184	19540.64	9789.763	9789.763	19579.53
COBB	39342.8	16861.15	56203.95	33724.65	22483.1	56207.75
COWETA	37567.29	4174.133	41741.42	29251.14	12536.2	41787.34
DEKLAB	38094.5	22276.75	60371.25	30164.24	30164.24	60328.48
DOUGLAS	40148.71	6373.543	46522.25	32590.38	13967.31	46557.69
FAYETTE	22268.47	2474.266	24742.73	17328.36	7426.438	24754.79
FORSYTH	53271.33	5919.025	59190.36	41436.21	17758.38	59194.59
FULTON	78501.31	67956.3	146457.6	73537.56	73537.56	147075.1
GWINNET	86221.77	36952.12	123173.9	73896.13	49264.08	123160.2
HENRY	74684.89	8298.306	82983.2	58155.87	24923.94	83079.81
PAULDING	41264.3	4584.911	45849.21	32065.45	13742.34	45807.79
ROCKDALE	21685.92	3183.245	24869.16	17441.46	7474.913	24916.38
TOTAL 13 COUNTY	614617.6	192459	807076.6	502204.9	305707	807911.9

Appendix I: Calculating the PV surface area factor



$$PV \text{ surface area factor} = \frac{2}{\sqrt{3} + separation\ factor}$$

Appendix J: Carbon Tax pricing over a 25-year period for low, default, amd high pricing estimates.

This study assumed the default pricing estimate for the Carbon tax.

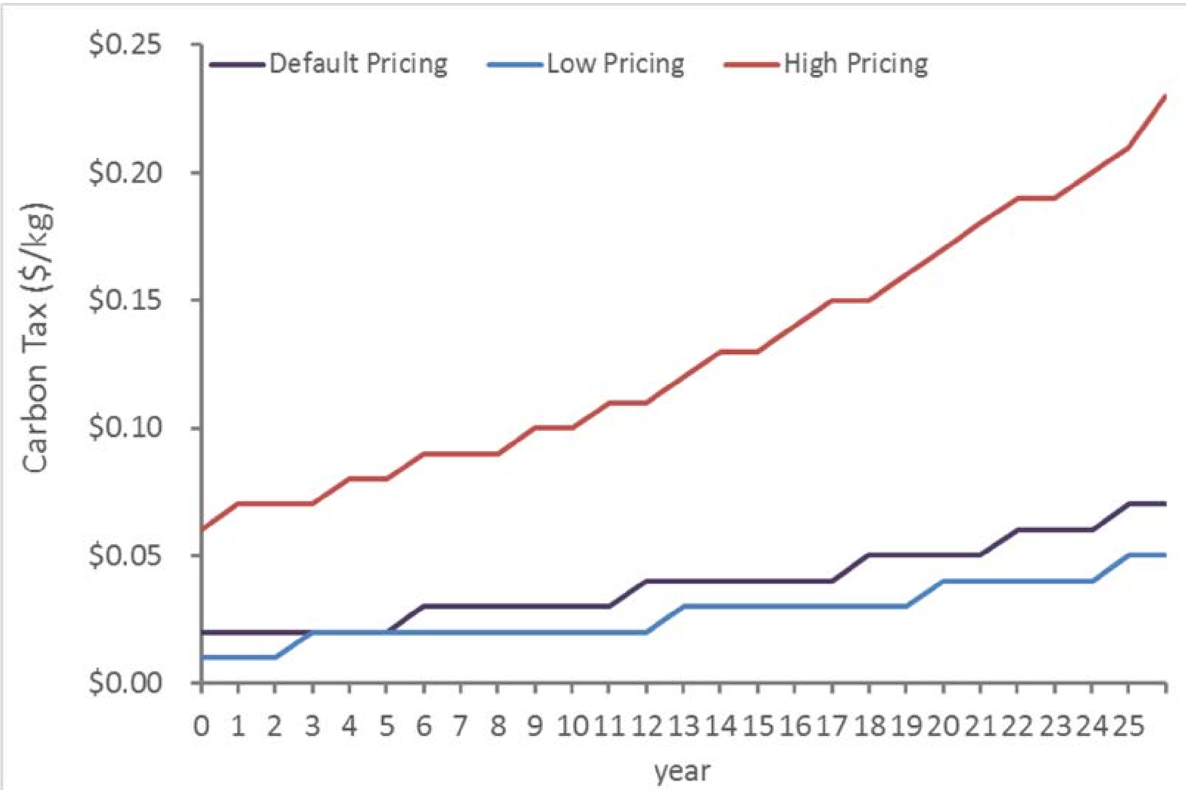


Figure 42: Tiered carbon tax pricing over a 25-year period.

Appendix K: NPV of implementing PV systems on the usable roof area for building prototypes in Atlanta.

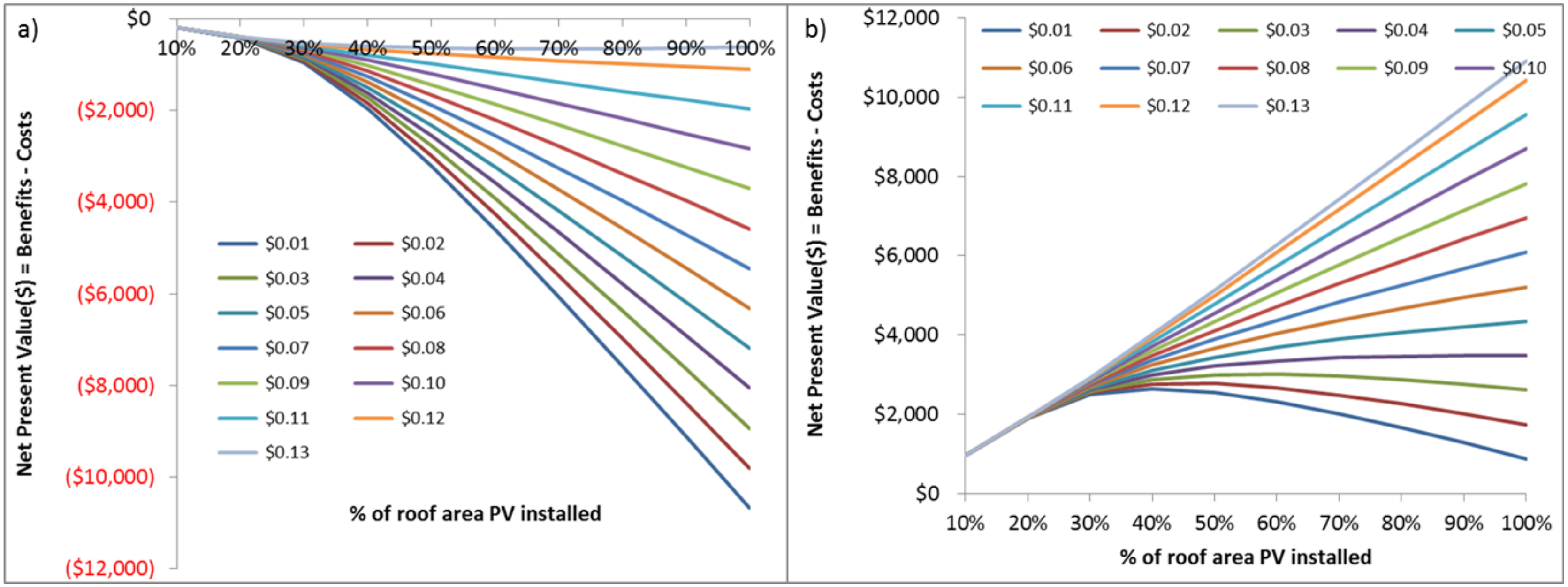


Figure 43: Net present value of implementing various sized PV systems for a single family residential building. a) Net present value of implementing PV system for a single- family residential building assuming discount rate of 5% and a PV system cost of $2.95/W. b) Net present value of implementing PV for a single family residential building with a PV system cost of $1/Watt.

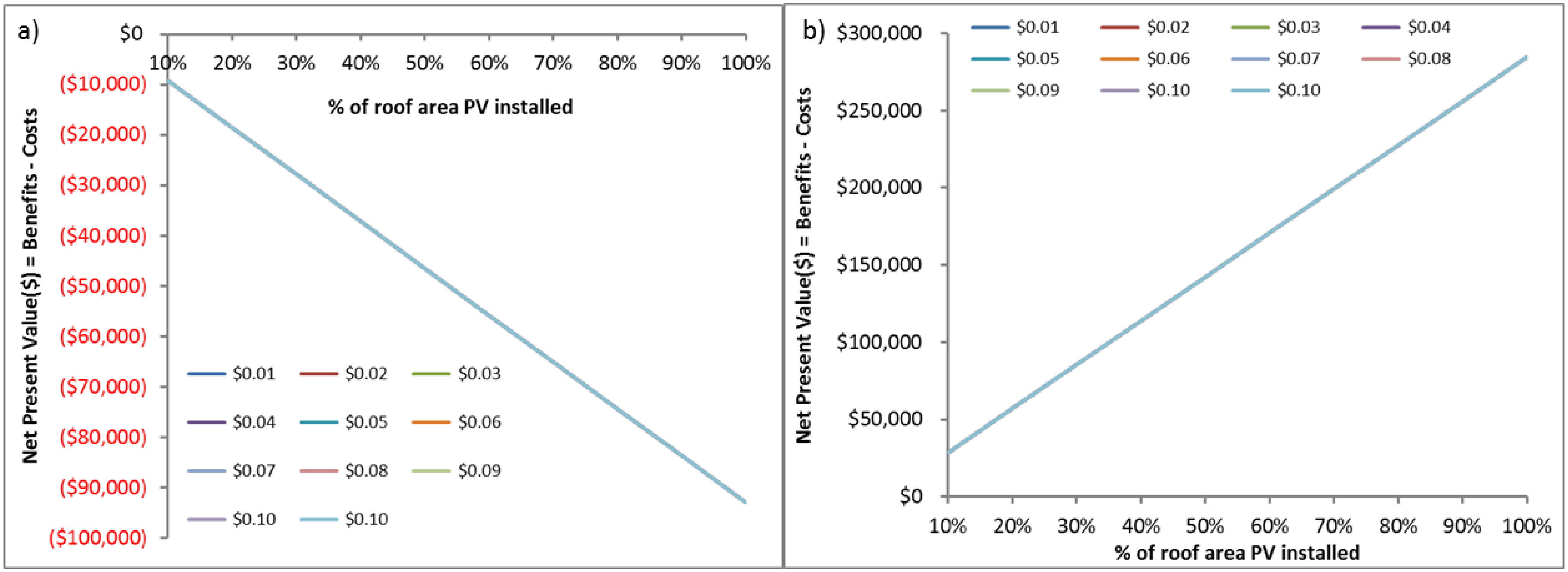


Figure 44: Net present value of implementing various sized PV systems for a large office building. a) Net present value of implementing PV system for a large office building assuming discount rate of 5% and a PV system cost of $2.95/W. b) Net present value of implementing PV for a large office building assuming discount rate of 5% and PV system cost of $1/W.

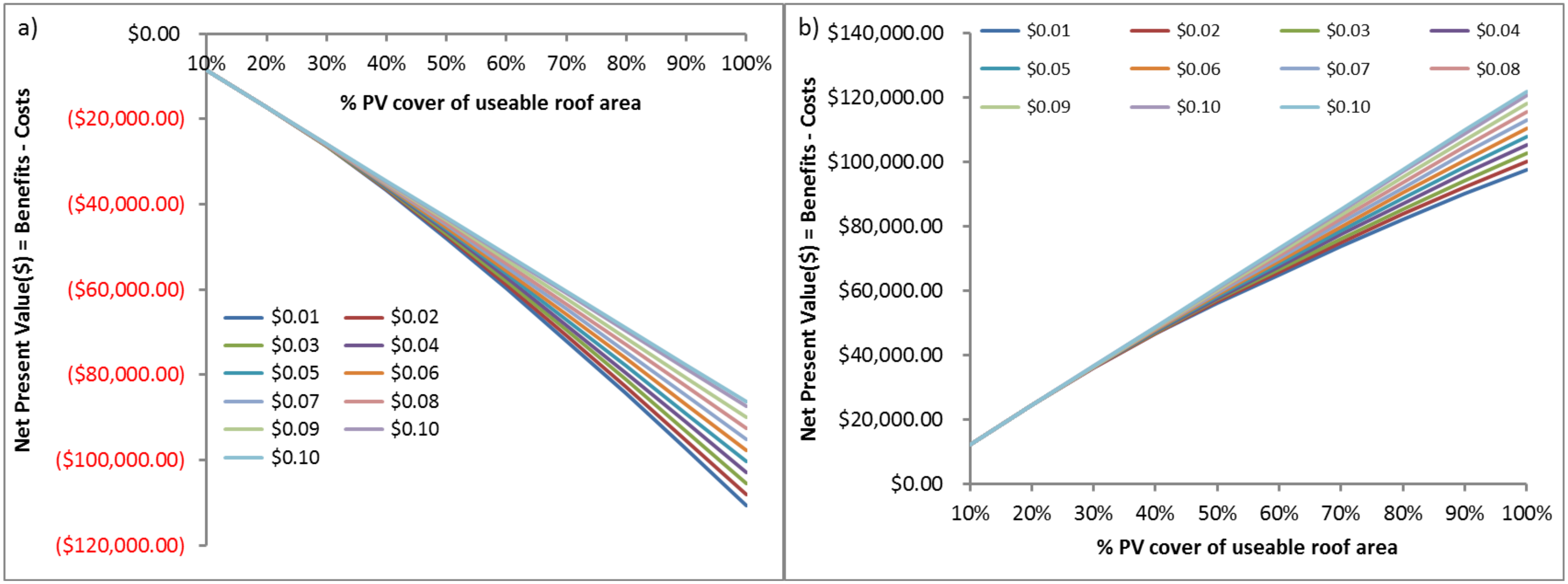


Figure 45: Net present value of implementing various sized PV systems for a medium office building. a) Net present value of implementing PV system for a medium office building assuming discount rate of 5% and a PV system cost of $2.95/W. b) Net present value of implementing PV for a medium office building assuming discount rate of 5% and PV system cost of $1/W.

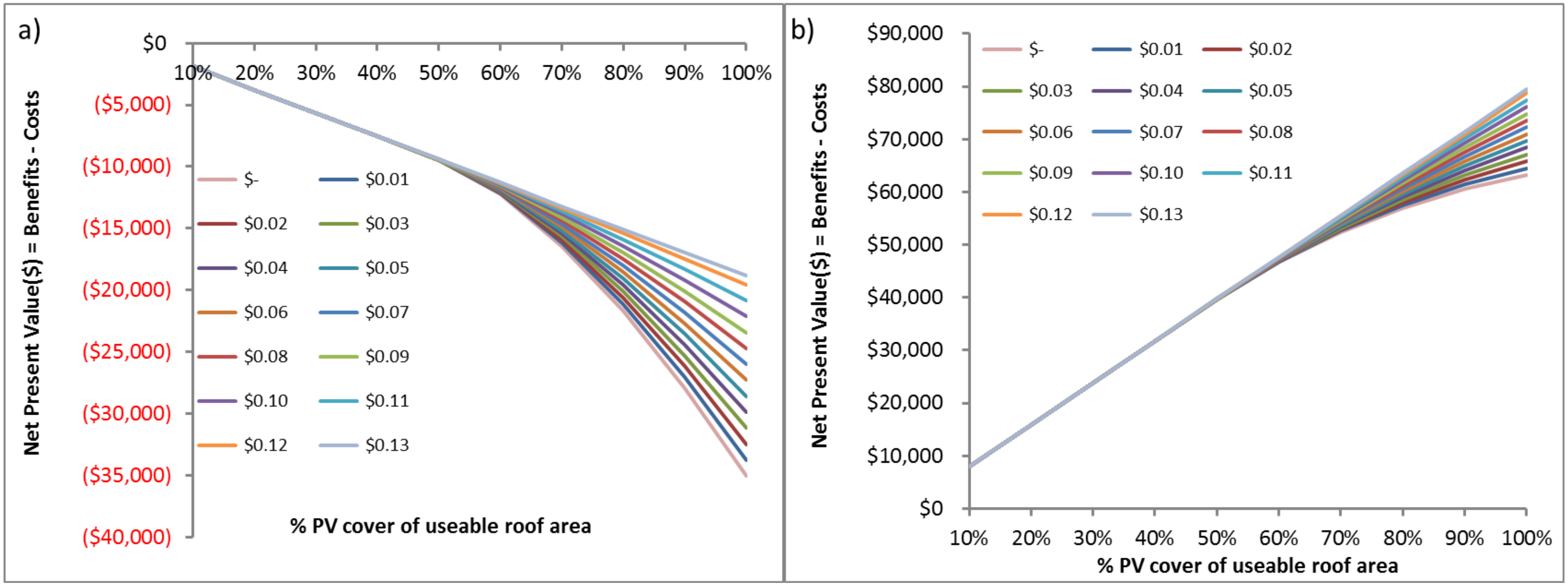


Figure 46: Net present value of implementing various sized PV systems for a multifamily residential building. a) Net present value of implementing PV system for a multifamily residential building assuming discount rate of 5% and a PV system cost of $2.95/W. b) Net present value of implementing PV for a multifamily residential building assuming discount rate of 5% and PV system cost of $1/W.

Appendix L: Annual avoided electricity savings with a hybrid PV-CCHP system.

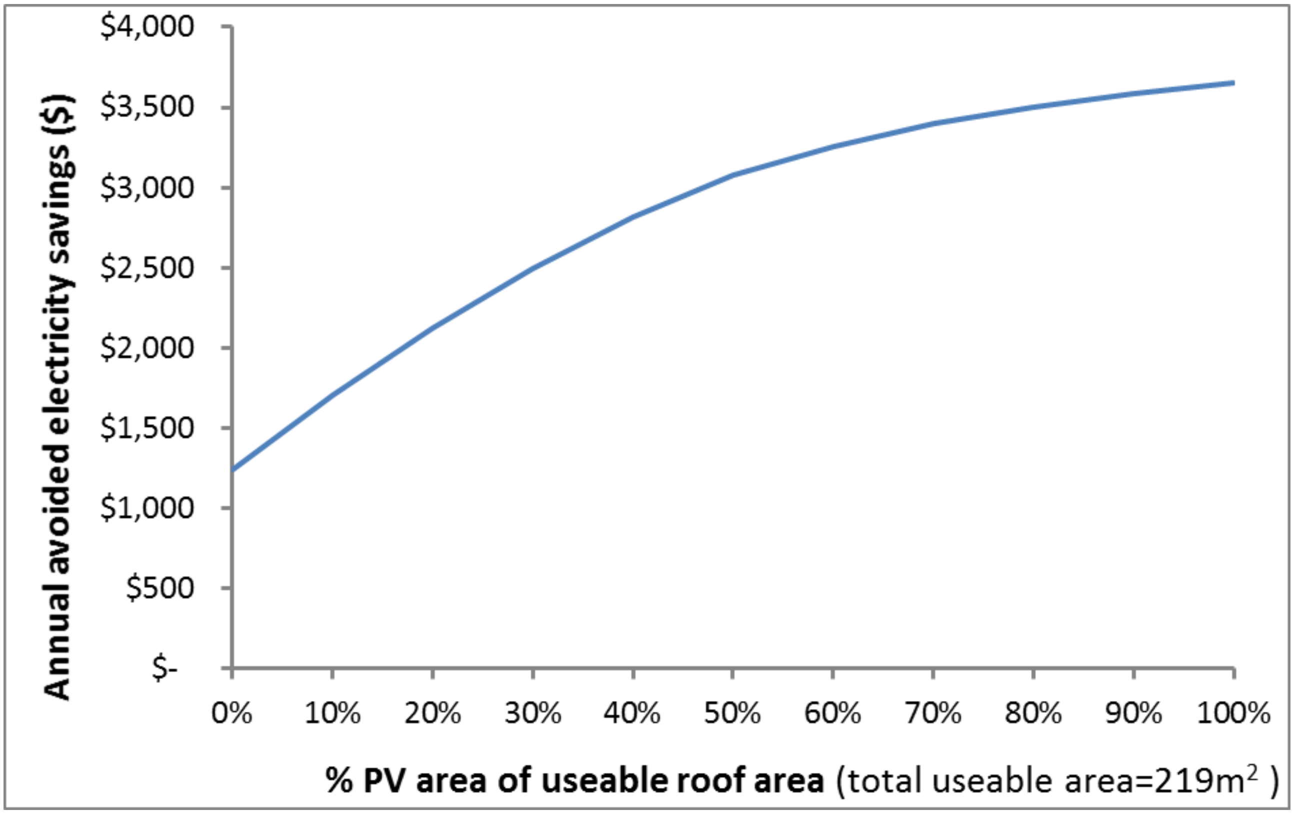


Figure 47: Annual avoided electricity costs for a small office building

Appendix M: Annual feed-in tariff benefits for a small office building.

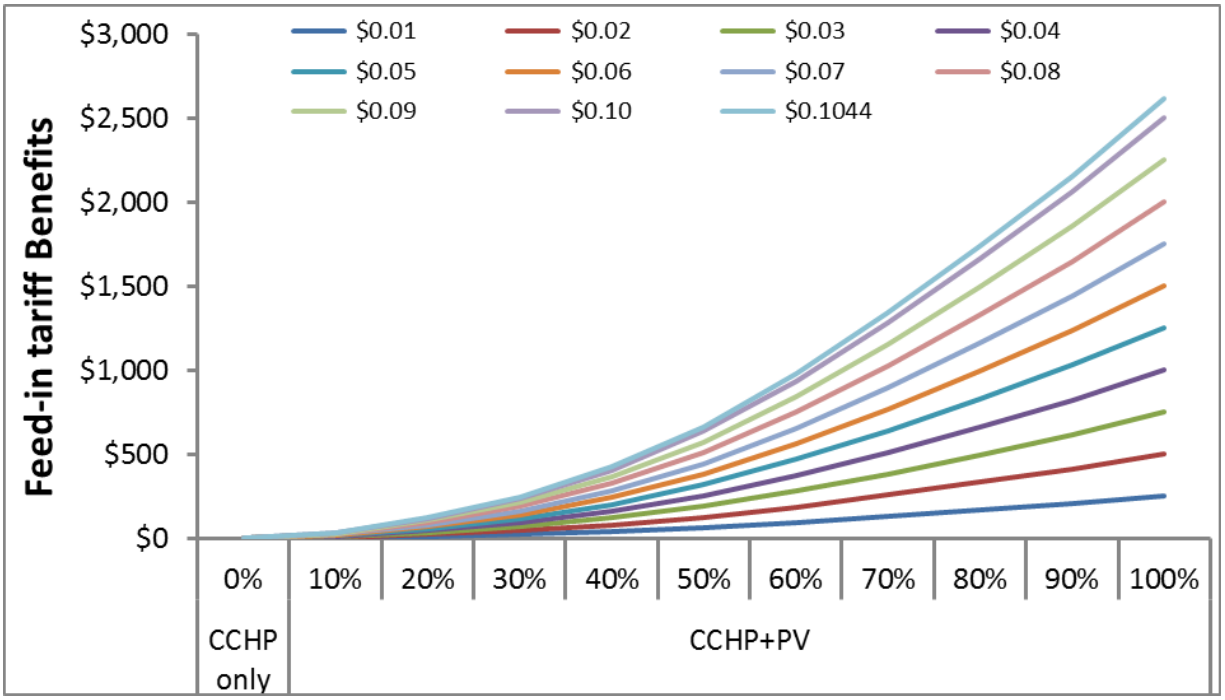


Figure 48: Annual feed-in tariff benefits for a small office building over the range of feed-in tariff rates

Appendix N: Annual damage cost savings from mitigating NOx production.

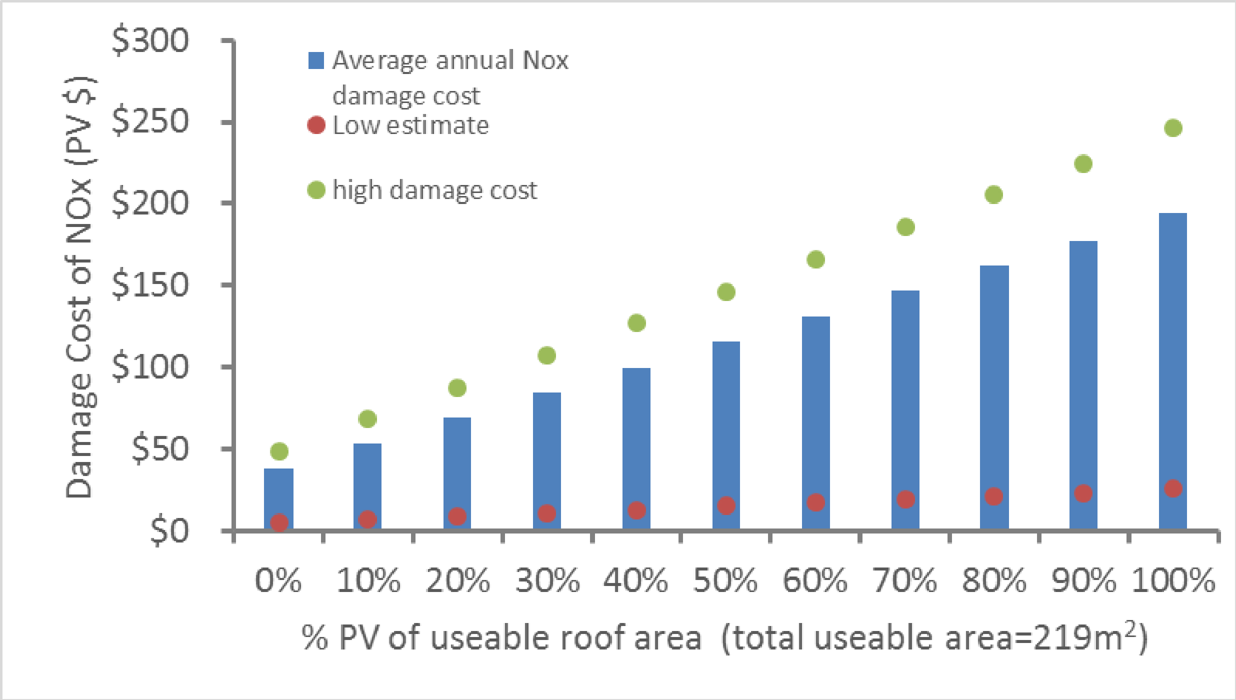


Figure 49: Annual damage cost savings from mitigating NOx production for a small office building.

Appendix O: Annual emissions (CO2, NOX) and water consumption savings with a PV-only and hybrid PV-CCHP system..

Table 8: Change in the water for energy consumption for varying percent PV coverage of the useable roof area.

Total avoided water for energy (gallons)	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Small office	7896.322	15792.64	23688.97	31585.29	39481.61	47377.93	55274.25	63170.58	71066.9	79567.58
Medium office	25664.48	51328.96	76993.45	102657.9	128322.4	153986.9	179651.4	205315.9	230980.3	256644.8
Large office	59820.62	119641.2	179461.9	239282.5	299103.1	358923.7	418744.3	478565	538385.6	598206.2
MF Residential	12110.09	24220.17	36330.26	48440.35	60550.43	72660.52	84770.61	96880.69	108990.8	121100.9
SF Residential	1827.64	3655.279	5482.919	7310.558	9138.198	10965.84	12793.48	14621.12	16448.76	18276.4

Table 9: Water consumption savings for energy generation with a CCHP system

GALLONS/ YEAR	CCHP ONLY	CCHP+%PV USEABLE ROOF AREA									
%PV USEABLE ROOF AREA	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
SMALL OFFICE	19567	27463	35360	43256	51152	59049	66945	74841	82738	90634	99135
MEDIUM OFFICE	279808	305472	331137	356801	382466	408130	433795	459459	485124	510788	536453
LARGE OFFICE	4786678	4846499	4906319	4966140	5025961	5085781	5145602	5205423	5265243	5325064	5384884
MF RESIDENTIAL	98515	110625	122735	134845	146955	159065	171176	183286	195396	207506	219616
SF RESIDENTIAL	7148	8975	10803	12631	14458	16286	18114	19941	21769	23597	25424

Table 10: Avoided NOx emissions for all building types with a PV-only system

Avoided NOx emissions (kg)	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Small office	2.0	3.9	5.9	7.8	9.8	11.7	13.7	15.6	17.6	19.7
Medium office	6.3	12.7	19.0	25.4	31.7	38.1	44.4	50.8	57.1	63.5
Large office	14.8	29.6	44.4	59.2	74.0	88.8	103.5	118.3	133.1	147.9
MF Residential	3.0	6.0	9.0	12.0	15.0	18.0	21.0	24.0	27.0	29.9
SF Residential	0.5	0.9	1.4	1.8	2.3	2.7	3.2	3.6	4.1	4.5

Table 11: NOx emissions savings from a CCHP and hybrid CCHP-PV system for all building prototypes

	CCHP only (kg)	*CCHP+PV (kg)*									
%PV useable roof area	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Small office	4.8	6.8	8.7	10.7	12.6	14.6	16.6	18.5	20.5	22.4	24.5
Medium office	69.2	75.5	81.9	88.2	94.6	100.9	107.3	113.6	120.0	126.3	132.7
Large office	1183.6	1198.4	1213.2	1228.0	1242.8	1257.6	1272.4	1287.2	1302.0	1316.7	1331.5
MF Residential	24.4	27.4	30.3	33.3	36.3	39.3	42.3	45.3	48.3	51.3	54.3
SF Residential	1.8	2.2	2.7	3.1	3.6	4.0	4.5	4.9	5.4	5.8	6.3

Table 12: CO_2 savings for all building types from a PV-only system

% useable PV area	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Small office	2709	5141	7422	9584	11647	13523	15080	16321	17277	18091
Medium office	8866	17732	26426	34509	42228	49733	57092	64301	71314	78148
Large office	20665	41331	61996	82661	103327	123992	144657	165322	185988	206653
MF Residential	4183	8367	12550	16734	20888	24797	28249	31339	34125	36613
SF Residential	631	1256	1747	2047	2252	2406	2528	2629	2718	2795

Table 13: Annual CO_2 emissions savings from a CCHP and hybrid CCHP-PV system for all building prototypes

	CCHP-Only	CCHP+PV									
% PV of useable roof area	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Small office	6760	9487	12215	14943	17671	20399	23126	25854	28582	31310	34247
Medium office	96661	105527	114393	123259	132125	140990	149856	158722	167588	176454	185320
Large office	1653580	1674245	1694910	1715576	1736241	1756906	1777572	1798237	1818902	1839567	1860233
MF Residential	34032	38216	42399	46583	50766	54950	59133	63317	67500	71684	75867
SF Residential	2469	3101	3732	4363	4995	5626	6257	6889	7520	8152	8783

1

APPENDIX P: Matlab Code for CCHP system sizing and operation based on the building energy demand

```
%%hourly demand
% read the data if not already here
if ~exist('labels','var');
    [num txt raw] = xlsread('turbine output.xlsx','Sheet1','B1:BI3');
    % arrange data
    labels = txt(1,1:end);
    percent = num(1,:);
    thermal_output = num(2:end,:);
end

% read the data if not already here
if ~exist('labels_elec','var');
    [num txt raw] = xlsread('turbine output.xlsx','Sheet2','B1:BI3');
    % arrange data
    labels_elec = txt(1,1:end);
    percent_elec = num(1,:);
    elec_output = num(2:end,:);
end

% read the demand data
if ~exist('demand','var');
    [demand date] = xlsread('medthermdmnd.xlsx','hourly','A3:B8762');
end

% read the demand data
if ~exist('hr_demand','var');
    [hr_demand, date] = xlsread('medthermdmnd.xlsx','hourly','A3:B8762');
end

% read the electrical demand data
if ~exist('elec_demand','var');
    [elec_demand, date] = xlsread('medthermdmnd.xlsx','elec','A3:B8762');
end

% water for energy multiplier (units: gal/kWh)
wtr4energy = 1.65;

%electricity emissions from power plant multiplier (units: kg CO2/ kWh)
gridemissions = 0.709;

%turbine CO2 emissions(units: kg CO2/ kWhe)
turb_emissions = 0.768;

%furnace CO2 emissions(units: kg CO2/ kWh)
furn_emissions = 0.227;

%elec grid NOx emissions(units: kg/ kWh)
```

```
gridNOx_emissions = 0.000681; %http://www.epa.gov/statelocalclimate/documents/pdf/ee-re_set-
asides_vol3.pdf

%furnace NOx emissions(units: kg/ kWh)
%[http://www.epa.state.il.us/air/aer/tables/conversion.html
%http://www.epa.gov/ttnchie1/ap42/ch01/final/c01s04.pdf -280lb/10^6scf
furnNOx_emissions = 0.000424941;

%turbine NOx emissions(units: kg/
%kWh)[http://www.multigen.com.au/wp-
content/themes/multigen/docs/410065B_Emissions_Tech_Ref.pdf]
turbNOx30_emissions = 0.00029056;
turbNOx65_emissions = 0.00020884;
turbNOx65L_emissions = 0.00007718; %low NOx turb
turbNOx200_emissions = 0.0001816;

%turbine NOx emissions(units: kg/ kWh)
turbVOC30_emissions = 0.00010442;
turbVOC65_emissions = 0.000045;
turbVOC200_emissions = 0.000045;
%MT emissions

% look at turbines
turbine_number = 1:60;

num_med_demand = length(hr_demand);
num_turbine = length(turbine_number);

% use this for UNIQUE turbine output
index = zeros(num_med_demand,1);
overmed_production=zeros(num_med_demand,1);
undermed_production=zeros(num_med_demand,1);
elecmed_overprod=zeros(num_med_demand,1);
elecmed_underprod=zeros(num_med_demand,1);
wtr4engy_med_elec=zeros(num_med_demand,1);
emissions_med_elec=zeros(num_med_demand,1);
emissions_med_therm=zeros(num_med_demand,1);
wtr4engy_med_netmet=zeros(num_med_demand,1);
emissions_med_netmet=zeros(num_med_demand,1);
emissions_med_totnetmet=zeros(num_med_demand,1);
emissions_med_no_totnetmet=zeros(num_med_demand,1);
emissions_med_elecNOx=zeros(num_med_demand,1);
emissions_med_thermNOx=zeros(num_med_demand,1);
emissions_med_NOx_netmet=zeros(num_med_demand,1);
emissions_med_NOx_nonetmet=zeros(num_med_demand,1);
for i = 1:num_med_demand
    s = thermal_output - hr_demand(i);
    s1 = s(s > 0);
    %[val, ind] = min(s1); % finds min demand that is < than output
        % ind2 = find(s1 == val); % if mulitple min, find all of them
   % index(i) = find(val == s);
```

```
    if any(s>0)
        [val, ind] = min(s1);
        index(i) = find(val == s);
    else
        [val, ind] = max(thermal_output);
       index(i)=ind(1);

    end

%     if s(index(i))>0
%         overmed_production(i)=s(index(i));
%     else
%         overmed_production(i)=0;
%     end
%     if s(index(i))<0
%         undermed_production(i)=s(index(i));
%     else
%         undermed_production(i)=0;
%     end
    if thermal_output(index(i))- demand (i)>0
        overmed_production(i)=thermal_output(index(i))- demand (i);
    else
        overmed_production(i)=0;
    end
    if thermal_output(index(i))- demand (i)<0
        undermed_production(i)= demand (i)- thermal_output(index(i));
    else
        undermed_production(i)=0;
    end
    if elec_output(index(i)) > elec_demand(i)
        elecmed_overprod (i)= elec_output(index(i)) - elec_demand(i);
    else
        elecmed_overprod (i)= 0;
    end
    if elec_demand(i) > elec_output(index(i))
        elecmed_underprod (i)= elec_demand(i) - elec_output (index(i));
    else
        elecmed_underprod (i)= 0;
    end
    wtr4engy_med_elec (i) = wtr4energy*elecmed_underprod (i);
    emissions_med_elec (i) = gridemissions*elecmed_underprod (i);
    emissions_med_therm (i) = turb_emissions*elec_output(index(i))+
(furn_emissions*undermed_production(i));
    emissions_med_elecNOx (i) = gridNOx_emissions*elecmed_underprod (i);
    emissions_med_thermNOx (i) = (turbNOx30_emissions*elec_output(index(i)))+
(furnNOx_emissions*undermed_production(i));
    wtr4engy_med_netmet (i) = (wtr4engy_med_elec (i)- (elecmed_overprod (i)*wtr4energy));
    emissions_med_netmet (i)= (emissions_med_elec (i)- (elecmed_overprod (i)*gridemissions));
    emissions_med_no_totnetmet (i)= (emissions_med_elec (i)+ emissions_med_therm (i)); %elec and
thermal emissions if no netmetering applicable
```

```
    emissions_med_totnetmet (i)= ( emissions_med_netmet (i)+ emissions_med_therm (i)); %elec and
thermal emissions if netmetering applicable
    emissions_med_NOx_nonetmet (i) = emissions_med_thermNOx (i)+ emissions_med_elecNOx (i) ;
%elec and thermal emissions if netmetering applicable
    emissions_med_NOx_netmet (i) = emissions_med_thermNOx (i)+ emissions_med_elecNOx (i) -
(elecmed_overprod (i)*gridNOx_emissions); %elec and thermal emissions if no netmetering applicable
end

% use this for possibly non unique turbine output
% index = cell(num_demand,1);
% for i = 1:num_demand
%     s = thermal_output - demand(i);
%     s1 = s(s > 0);
%     [val, ind] = min(s1); % finds min demand that is < than output
%     % ind2 = find(s1 == val); % if mulitple min, find all of them
%     index{i} = find(val == s);
% end

% stack the data
all_data = cell(num_med_demand,21);

% in the following, if non unique data, replace index(i) with index{i}
% (these are curly braces)
for i = 1:num_med_demand
    all_data(i,1) = date(i);
    all_data(i,2) = labels(index(i));
    all_data{i,3} = percent(index(i));
    all_data{i,4} = thermal_output(index(i));
    all_data{i,5} = hr_demand(i);
    all_data{i,6} = elec_output(index(i));
    all_data{i,7} = overmed_production(i);
    all_data{i,8} = undermed_production(i);
    all_data{i,9} = elecmed_overprod(i);
    all_data{i,10} = elecmed_underprod(i);
    all_data{i,11} = emissions_med_therm (i);
    all_data{i,12} = emissions_med_elec (i);
    all_data{i,14} = wtr4engy_med_elec (i);
    all_data{i,15} = elec_demand(i);
    all_data{i,16} = emissions_med_thermNOx (i);
    all_data{i,17} = emissions_med_elecNOx (i);
    all_data{i,18} = emissions_med_no_totnetmet (i);
    all_data{i,19} = emissions_med_totnetmet (i);
    all_data{i,20} = wtr4engy_med_netmet (i);
    all_data{i,21} = emissions_med_netmet (i);
    all_data{i,22} = emissions_med_NOx_nonetmet (i);
    all_data{i,23} = emissions_med_NOx_netmet (i);

end

% write data to an excel sheet
xlswrite ('medthermdmnd hr day month year.xls', all_data, 1, 'a3')
```

```
%% daily demand
% read the data if not already here
if ~exist('labels','var');
    [num txt raw] = xlsread('turbine output.xlsx','Sheet1','B1:BI3');
    % arrange data
    labels = txt(1,2:end);
    percent = num(1,:);
    thermal_output = num(2:end,:)';
end



% read the demand data
if ~exist('dly_demand','var');
    [dly_demand date] = xlsread('medthermdmnd.xlsx','daily','A3:B8762');
end


% look at turbines
turbine_number = 1:60;

num_demand = length(dly_demand);
num_turbine = length(turbine_number);

% use this for UNIQUE turbine output
index = zeros(num_demand,1);
over_production=zeros(num_demand,1);
under_production=zeros(num_demand,1);
elec_overprod=zeros(num_demand,1);
elec_underprod=zeros(num_demand,1);
wtr4engy_elec=zeros(num_demand,1);
emissions_elec=zeros(num_demand,1);
emissions_therm=zeros(num_demand,1);
wtr4engy_netmet=zeros(num_demand,1);
emissions_netmet=zeros(num_demand,1);
emissions_totnetmet=zeros(num_demand,1);
emissions_no_totnetmet=zeros(num_demand,1);
emissions_elecNOx=zeros(num_med_demand,1);
emissions_thermNOx=zeros(num_med_demand,1);
emissions_NOx_netmet=zeros(num_med_demand,1);
emissions_NOx_nonetmet=zeros(num_med_demand,1);
for i = 1:num_demand
    s = thermal_output - dly_demand(i);
    s1 = s(s > 0);
    if any(s>0)
        [val, ind] = min(s1);
        index(i) = find(val == s);
    else
        [val, ind] = max(thermal_output);
       index(i)=ind(1);
```

```
    end

%     if s(index(i))>0
%         over_production(i)=s(index(i));
%     else
%         over_production(i)=0;
%     end
%     if s(index(i))<0
%         under_production(i)=s(index(i));
%     else
%         under_production(i)=0;
%     end
    if thermal_output(index(i))- dly_demand (i)>0
        over_production(i)=thermal_output(index(i))- dly_demand (i);
    else
        over_production(i)=0;
    end
    if thermal_output(index(i))- dly_demand (i)<0
        under_production(i)= dly_demand (i)- thermal_output(index(i));
    else
        under_production(i)=0;
    end
    if elec_output(index(i)) > elec_demand(i)
        elec_overprod (i)= elec_output(index(i)) - elec_demand(i);
    else
        elec_overprod (i)= 0;
    end
    if elec_demand(i) > elec_output(index(i))
        elec_underprod (i)= elec_demand(i) - elec_output (index(i));
    else
        elec_underprod (i)= 0;
    end
    wtr4engy_elec (i) = wtr4energy*elec_underprod (i);
    emissions_elec (i) = gridemissions*elec_underprod (i);
    emissions_therm (i) = (turb_emissions*elec_output(index(i)))+ (furn_emissions*under_production(i));
    emissions_elecNOx (i) = gridNOx_emissions*elec_underprod (i);
    emissions_thermNOx (i) = (turbNOx30_emissions*elec_output(index(i)))+
(furnNOx_emissions*under_production(i));
    wtr4engy_netmet (i) = (wtr4engy_elec (i)- (elec_overprod (i)*wtr4energy));
    emissions_netmet (i)= (emissions_elec (i)- (elec_overprod (i)*gridemissions));
    emissions_no_totnetmet (i)= (emissions_elec (i)+ emissions_therm (i)); %elec and thermal emissions if
no netmetering applicable
    emissions_totnetmet (i)= ( emissions_netmet (i)+ emissions_therm (i)); %elec and thermal emissions if
netmetering applicable
    emissions_NOx_nonetmet (i) = emissions_thermNOx (i)+ emissions_elecNOx (i) ; %elec and thermal
emissions if netmetering applicable
    emissions_NOx_netmet (i) =  emissions_NOx_nonetmet (i) - (elecmed_overprod
(i)*gridNOx_emissions); %elec and thermal emissions if no netmetering applicable
end
```

```
% use this for possibly non unique turbine output
% index = cell(num_demand,1);
% for i = 1:num_demand
%     s = thermal_output - demand(i);
%     s1 = s(s > 0);
%     [val, ind] = min(s1); % finds min demand that is < than output
%     % ind2 = find(s1 == val); % if mulitple min, find all of them
%     index{i} = find(val == s);
% end

% stack the data
all_data = cell(num_demand,21);

% in the following, if non unique data, replace index(i) with index{i}
% (these are curly braces)
for i = 1:num_demand
    all_data(i,1) = date(i);
    all_data(i,2) = labels(index(i));
    all_data{i,3} = percent(index(i));
    all_data{i,4} = thermal_output(index(i));
    all_data{i,5} = dly_demand(i);
    all_data{i,6} = elec_output(index(i));
    all_data{i,7} = over_production(i);
    all_data{i,8} = under_production(i);
    all_data{i,9} = elec_overprod(i);
    all_data{i,10} = elec_underprod(i);
    all_data{i,11} = emissions_therm (i);
    all_data{i,12} = emissions_elec (i);
    all_data{i,14} = wtr4engy_elec (i);
    all_data{i,15} = elec_demand(i);
    all_data{i,16} = emissions_thermNOx (i);
    all_data{i,17} = emissions_elecNOx (i);
    all_data{i,18} = emissions_no_totnetmet (i);
    all_data{i,19} = emissions_totnetmet (i);
    all_data{i,20} = wtr4engy_netmet (i);
    all_data{i,21} = emissions_netmet (i);
    all_data{i,22} = emissions_NOx_nonetmet (i);
    all_data{i,23} = emissions_NOx_netmet (i);
end

% write data to an excel sheet
xlswrite ('medthermdmnd hr day month year.xls', all_data, 2, 'a3')

%% monthly demand
% read the data if not already here
if ~exist('num','var');
    [num txt raw] = xlsread('turbine output.xlsx','Sheet1','B1:BI3');
    % arrange data
    labels = txt(1,2:end);
    percent = num(1,:);
    thermal_output = num(2:end,:)';
```

```
end



% read the demand data
if ~exist('mnth_demand','var');
   [mnth_demand date] = xlsread('medthermdmnd.xlsx','monthly','A3:B8762');
end


% look at turbines
turbine_number = 1:60;

num_mnth_demand = length(mnth_demand);
num_turbine = length(turbine_number);

% use this for UNIQUE turbine output
index = zeros(num_mnth_demand,1);
overmax_production=zeros(num_mnth_demand,1);
undermax_production=zeros(num_mnth_demand,1);
elecmax_overprod=zeros(num_mnth_demand,1);
elecmax_underprod=zeros(num_mnth_demand,1);
wtr4engy_max_elec=zeros(num_mnth_demand,1);
emissions_max_elec=zeros(num_mnth_demand,1);
emissions_max_therm=zeros(num_mnth_demand,1);
wtr4engy_max_netmet=zeros(num_mnth_demand,1);
emissions_max_netmet=zeros(num_mnth_demand,1);
emissions_max_totnetmet=zeros(num_mnth_demand,1);
emissions_max_no_totnetmet=zeros(num_mnth_demand,1);
emissions_max_elecNOx=zeros(num_mnth_demand,1);
emissions_max_thermNOx=zeros(num_mnth_demand,1);
emissions_max_NOx_netmet=zeros(num_mnth_demand,1);
emissions_max_NOx_nonetmet=zeros(num_mnth_demand,1);
for i = 1:num_mnth_demand
   s = thermal_output - mnth_demand(i);
   s1 = s(s > 0);
   if any(s>0)
      [val, ind] = min(s1);
      index(i) = find(val == s);
   else
      [val, ind] = max(thermal_output);
     index(i)=ind(1);

   end

%    if s(index(i))>0
%       overmax_production(i)=s(index(i));
%    else
%       overmax_production(i)=0;
%    end
%    if s(index(i))<0
```

```
%         undermax_production(i)=s(index(i));
%     else
%         undermax_production(i)=0;
%     end
    if thermal_output(index(i))- mnth_demand (i)>0
        overmax_production(i)=thermal_output(index(i))- mnth_demand (i);
    else
        overmax_production(i)=0;
    end
    if thermal_output(index(i))- mnth_demand (i)<0
        undermax_production(i)= mnth_demand (i)- thermal_output(index(i));
    else
        undermax_production(i)=0;
    end
    if elec_output(index(i)) > elec_demand(i)
        elecmax_overprod (i)= elec_output(index(i)) - elec_demand(i);
    else
        elecmax_overprod (i)= 0;
    end
    if elec_demand(i) > elec_output(index(i))
        elecmax_underprod (i)= elec_demand(i) - elec_output (index(i));
    else
        elecmax_underprod (i)= 0;
    end
    wtr4engy_max_elec (i) = wtr4energy*elecmax_underprod (i);
    emissions_max_elec (i) = gridemissions*elecmax_underprod (i);
    emissions_max_therm (i) = (turb_emissions*elec_output(index(i)))+
(furn_emissions*undermax_production(i));
    emissions_max_elecNOx (i) = gridNOx_emissions*elecmax_underprod (i);
    emissions_max_thermNOx (i) = (turbNOx30_emissions*elec_output(index(i)))+
(furnNOx_emissions*undermax_production(i));
    wtr4engy_max_netmet (i) = (wtr4engy_max_elec (i)- (elecmax_overprod (i)*wtr4energy));
    emissions_max_netmet (i)= (emissions_max_elec (i)- (elecmax_overprod (i)*gridemissions));
    emissions_max_no_totnetmet (i)= (emissions_max_elec (i)+ emissions_max_therm (i)); %elec and
thermal emissions if no netmetering applicable
    emissions_max_totnetmet (i)= ( emissions_max_netmet (i)+ emissions_max_therm (i)); %elec and
thermal emissions if netmetering applicable
    emissions_max_NOx_nonetmet (i) = emissions_max_thermNOx (i)+ emissions_max_elecNOx (i) ;
%elec and thermal emissions if netmetering applicable
    emissions_max_NOx_netmet (i) =  emissions_max_NOx_nonetmet (i) - (elecmax_overprod
(i)*gridNOx_emissions); %elec and thermal emissions if no netmetering applicable
end

% use this for possibly non unique turbine output
% index = cell(num_demand,1);
% for i = 1:num_demand
%     s = thermal_output - demand(i);
%     s1 = s(s > 0);
%     [val, ind] = min(s1); % finds min demand that is < than output
%     % ind2 = find(s1 == val); % if mulitple min, find all of them
%     index{i} = find(val == s);
```

```
% end

% stack the data
all_data = cell(num_mnth_demand,21);

% in the following, if non unique data, replace index(i) with index{i}
% (these are curly braces)
for i = 1:num_mnth_demand
    all_data(i,1) = date(i);
    all_data(i,2) = labels(index(i));
    all_data{i,3} = percent(index(i));
    all_data{i,4} = thermal_output(index(i));
    all_data{i,5} = mnth_demand(i);
    all_data{i,6} = elec_output(index(i));
    all_data{i,7} = overmax_production(i);
    all_data{i,8} = undermax_production(i);
    all_data{i,9} = elecmax_overprod(i);
    all_data{i,10} = elecmax_underprod(i);
    all_data{i,11} = emissions_max_therm (i);
    all_data{i,12} = emissions_max_elec (i);
    all_data{i,14} = wtr4engy_max_elec (i);
    all_data{i,15} = elec_demand(i);
    all_data{i,16} = emissions_max_thermNOx (i);
    all_data{i,17} = emissions_max_elecNOx (i);
    all_data{i,18} = emissions_max_no_totnetmet (i);
    all_data{i,19} = emissions_max_totnetmet (i);
    all_data{i,20} = wtr4engy_max_netmet (i);
    all_data{i,21} = emissions_max_netmet (i);
    all_data{i,22} = emissions_max_NOx_nonetmet (i);
    all_data{i,23} = emissions_max_NOx_netmet (i);
end

% write data to an excel sheet
xlswrite ('medthermdmnd hr day month year.xls', all_data, 3, 'a3')

%% yearly demand

% read the data if not already here
if ~exist('num','var');
    [num txt raw] = xlsread('turbine output.xlsx','Sheet1','B1:BI3');
    % arrange data
    labels = txt(1,2:end);
    percent = num(1,:);
    thermal_output = num(2:end,:)';
end



% read the demand data
if ~exist('q3_demand','var');
    [q3_demand date] = xlsread('medthermdmnd.xlsx','yearly','A3:B8762');
```

```
end


% look at turbines
turbine_number = 1:60;

num_q3_demand = length(q3_demand);
num_turbine = length(turbine_number);
overq3_production=zeros(num_q3_demand,1);
underq3_production=zeros(num_q3_demand,1);
elecq3_overprod=zeros(num_q3_demand,1);
elecq3_underprod=zeros(num_q3_demand,1);
wtr4engy_q3_elec=zeros(num_q3_demand,1);
emissions_q3_elec=zeros(num_q3_demand,1);
emissions_q3_therm=zeros(num_q3_demand,1);
wtr4engy_q3_netmet=zeros(num_q3_demand,1);
emissions_q3_netmet=zeros(num_q3_demand,1);
emissions_q3_totnetmet=zeros(num_q3_demand,1);
emissions_q3_no_totnetmet=zeros(num_q3_demand,1);
emissions_q3_elecNOx=zeros(num_q3_demand,1);
emissions_q3_thermNOx=zeros(num_q3_demand,1);
emissions_q3_NOx_netmet=zeros(num_q3_demand,1);
emissions_q3_NOx_nonetmet=zeros(num_q3_demand,1);
% use this for UNIQUE turbine output
index = zeros(num_q3_demand,1);
for i = 1:num_q3_demand
   s = thermal_output - q3_demand(i);
   s1 = s(s > 0);
   if any(s>0)
      [val, ind] = min(s1);
      index(i) = find(val == s);
   else
      [val, ind] = max(thermal_output);
     index(i)=ind(1);

   end


%    if s(index(i))>0
%        overq3_production(i)=s(index(i));
%    else
%        overq3_production(i)=0;
%    end
%    if s(index(i))<0
%        underq3_production(i)=s(index(i));
%    else
%        underq3_production(i)=0;
%    end
   if thermal_output(index(i))- demand (i)<0
      underq3_production(i)= demand (i)- thermal_output(index(i));
   else
```

```
        underq3_production(i)=0;
    end
    if elec_output(index(i)) > elec_demand(i)
        elecq3_overprod (i)= elec_output(index(i)) - elec_demand(i);
    else
        elecq3_overprod (i)= 0;
    end
    if elec_output(index(i)) > elec_demand(i)
        elecq3_overprod (i)= elec_output(index(i)) - elec_demand(i);
    else
        elecq3_overprod (i)= 0;
    end
    if elec_demand(i) > elec_output(index(i))
        elecq3_underprod (i)= elec_demand(i) - elec_output (index(i));
    else
        elecq3_underprod (i)= 0;
    end
    wtr4engy_q3_elec (i) = wtr4energy*elecq3_underprod (i);
    emissions_q3_elec (i) = gridemissions*elecq3_underprod (i);
    emissions_q3_therm (i) = (turb_emissions*elec_output(index(i)))+
(furn_emissions*underq3_production(i));
    emissions_q3_elecNOx (i) = gridNOx_emissions*elecq3_underprod (i);
    emissions_q3_thermNOx (i) = (turbNOx30_emissions*elec_output(index(i)))+
(furnNOx_emissions*underq3_production(i));
    wtr4engy_q3_netmet (i) = (wtr4engy_q3_elec (i)- (elecq3_overprod (i)*wtr4energy));
    emissions_q3_netmet (i)= (emissions_q3_elec (i)- (elecq3_overprod (i)*gridemissions));
    emissions_q3_no_totnetmet (i)= (emissions_q3_elec (i)+ emissions_q3_therm (i)); %elec and thermal
emissions if no netmetering applicable
    emissions_q3_totnetmet (i)= ( emissions_q3_netmet (i)+ emissions_q3_therm (i)); %elec and thermal
emissions if netmetering applicable
    emissions_q3_NOx_nonetmet (i) = emissions_q3_thermNOx (i)+ emissions_q3_elecNOx (i) ; %elec
and thermal emissions if netmetering applicable
    emissions_q3_NOx_netmet (i) =  (emissions_q3_NOx_nonetmet (i) - (elecq3_overprod
(i)*gridNOx_emissions)); %elec and thermal emissions if no netmetering applicable
end

% use this for possibly non unique turbine output
% index = cell(num_demand,1);
% for i = 1:num_demand
%     s = thermal_output - demand(i);
%     s1 = s(s > 0);
%     [val, ind] = min(s1); % finds min demand that is < than output
%     % ind2 = find(s1 == val); % if mulitple min, find all of them
%     index{i} = find(val == s);
% end

% stack the data
all_data = cell(num_q3_demand,21);

% in the following, if non unique data, replace index(i) with index{i}
% (these are curly braces)
```

```
for i = 1:num_q3_demand
    all_data(i,1) = date(i);
    all_data(i,2) = labels(index(i));
    all_data{i,3} = percent(index(i));
    all_data{i,4} = thermal_output(index(i));
    all_data{i,5} = q3_demand(i);
    all_data{i,6} = elec_output(index(i));
    all_data{i,7} = overq3_production(i);
    all_data{i,8} = underq3_production(i);
    all_data{i,9} = elecq3_overprod(i);
    all_data{i,10} = elecq3_underprod(i);
    all_data{i,11} = emissions_q3_therm (i);
    all_data{i,12} = emissions_q3_elec (i);
    all_data{i,14} = wtr4engy_q3_elec (i);
    all_data{i,15} = elec_demand(i);
    all_data{i,16} = emissions_q3_thermNOx (i);
    all_data{i,17} = emissions_q3_elecNOx (i);
    all_data{i,18} = emissions_q3_no_totnetmet (i);
    all_data{i,19} = emissions_q3_totnetmet (i);
    all_data{i,20} = wtr4engy_q3_netmet (i);
    all_data{i,21} = emissions_q3_netmet (i);
    all_data{i,22} = emissions_q3_NOx_nonetmet (i);
    all_data{i,23} = emissions_q3_NOx_netmet (i);
end

% write data to an excel sheet
xlswrite ('medthermdmnd hr day month year.xls', all_data, 4, 'a3')
```

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